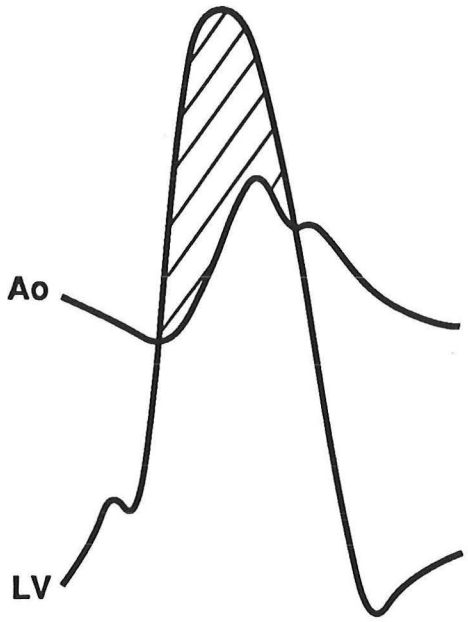
Hemodynamic Assessment of Aortic Stenosis



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The decision to operate in patients with aortic stenosis is based on the demonstration of hemodynamically significant valvular obstruction in symptomatic patients. Because clinical evaluation of the severity of aortic stenosis may be difficult, particularly in elderly patients, the degree of valvular obstruction has traditionally been determined by calculation of aortic valve area at cardiac catheterization. Recently, Doppler echocardiography has been shown to accurately calculate aortic valve area in patients with aortic stenosis. Accordingly, several investigators have proposed that catheterization is no longer necessary to assess the need for surgical intervention in most patients with aortic stenosis [1-4]. Others have suggested that while Doppler estimates of aortic valve area are generally concordant with catheterization, disparities exist in enough cases that invasive determination of aortic valve area should still be performed before aortic valve replacement [5,6]. Accordingly, the objectives of these Grand Rounds are to:

1) review the natural history and clinical characteristics of aortic stenosis,
2) evaluate the hemodynamic aspects of aortic stenosis, including the strengths and weaknesses of both cardiac catheterization and Doppler echocardiography in determining aortic valve area, and
3) examine the concept of "critical AS" and its implications regarding selection of patients for surgical intervention.

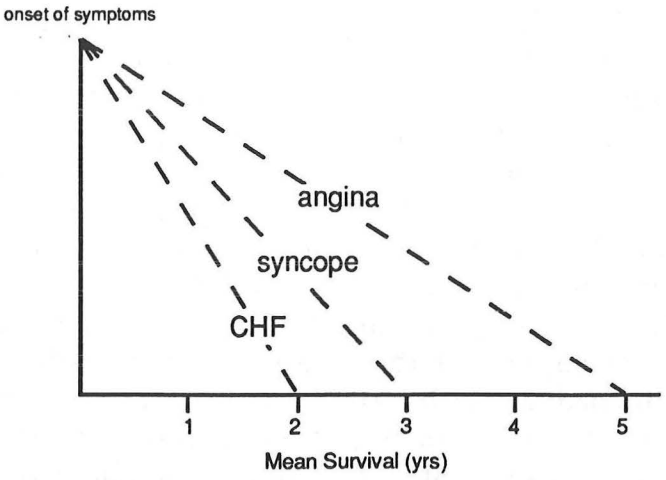
Etiology

The etiology of valvular aortic stenosis involves three pathologic mechanisms. In 1973, Roberts reported that two-thirds of all cases of valvular aortic stenosis in adults were due to a congenitally bicuspid valve [7]. The remaining one-third of cases was evenly divided between rheumatic and degenerative aortic stenosis. More recent data from the Mayo Clinic show that degenerative aortic stenosis is now the most common form of aortic stenosis, presumably due to increasing age of the population and a decline in rheumatic fever [8]. Regardless of etiology, aortic stenosis results in slowly progressive obstruction of the valve orifice due to calcification and/or fibrosis with symptoms occurring late in the course of the disease, usually years after the identification of a murmur [9-13].

Natural History

In 1968, Ross and Braunwald [13] reviewed seven autopsy studies published prior to 1955, and suggested that the mean survival after the onset of symptoms was 5 years for angina, 3 years for syncope, and 2 years for congestive heart failure (fig 1). Several subsequent studies have confirmed that medical treatment of symptomatic severe aortic stenosis is associated with a poor prognosis. Horstkotte and Loogen [14] prospectively followed 35 patients with symptomatic severe aortic stenosis who had refused surgery. Average survival was 23 months, 45 months for angina, 27 months for syncope, and 11 months for congestive heart failure. Frank, et al [15] studied 15 such patients in whom the mortality rates were 36%, 52%, and 90% at 3, 5, and 10 years, respectively. Chizner, et al [16] reported 1,2,5, and 11 year mortality rates of 26%, 48%, 64%, and 94% for 23 subjects with medically treated symptomatic aortic

stenosis. Rapaport [17] studied 40 similar patients with 5 and 10 year mortality rates of 62% and 80%, respectively. Schwartz, et al [18] reported a 3 year mortality of 79% in 19 patients who had refused surgery for symptomatic aortic stenosis. O'Keefe, et al [19] studied 50 patients with symptomatic aortic stenosis treated medically with 1, 2, and 3 year mortality rates of 43%, 63%, and 75%. *Thus, it is clear that the prognosis for medically treated symptomatic severe aortic stenosis is very poor.*



Clinical Manifestations

The clinical findings in aortic stenosis include a systolic ejection murmur that peaks later in systole or is prolonged in duration with increasing severity of aortic stenosis, diminished or delayed carotid upstrokes, a narrow pulse pressure, absence of the second heart sound, and an S4 gallop [9-13]. Such findings, although indicative of the presence of aortic stenosis, are not sufficiently accurate in predicting the hemodynamic severity of the lesion, particularly in patients over the age of sixty. Lombard and Selzer [11] reviewed the clinical and hemodynamic data of 397 subjects with a mean age of 61, 87% of whom had aortic valve areas of less than 1 cm^2 at catheterization. The absence of a second heart sound was noted in only 8.8% of patients, and a narrow pulse pressure in only 2.8%. In addition, 10.4% had a systolic ejection murmur that was only Grade I-II in intensity. Aronow and Kronzon [20] studied 781 elderly patients, 142 of whom had aortic stenosis, and concluded that the physical examination was of limited value in distinguishing between moderate and severe aortic stenosis.

The ECG typically shows evidence of left ventricular hypertrophy with or without repolarization abnormalities. Left atrial enlargement may also be present. Conduction abnormalities may occur, particularly in the setting of severe calcific aortic stenosis. Ventricular ectopy is common. The chest x-ray is generally normal, although cardiomegaly may be seen in patients with associated aortic regurgitation or left ventricular failure.

Hemodynamics

The normal aortic valve area is about 3-4 cm^2. In aortic stenosis, the aortic valve becomes progressively narrowed at an average rate of about 0.1 cm^2 per year [21]. With progressive reduction in valve orifice area, a systolic pressure gradient develops between the left ventricle and the aorta in order to maintain flow across the narrowed aortic valve orifice. The increased left ventricular pressure stimulates left ventricular hypertrophy which tends to normalize wall stress (afterload) [22,23].

Left ventricular end-systolic wall stress (σ_{es}) is assessed as:

$$\sigma_{es} = \frac{P \times r}{2h},$$

where P is pressure, r is chamber radius, and h is wall thickness. The relative normalization of afterload by left ventricular hypertrophy tends to preserve left ventricular contractile function even in the setting of severe aortic valvular obstruction. Thus, the majority of aortic stenosis patients have normal left ventricular cavity size and systolic function. However, some patients have an inadequate hypertrophic response such that afterload is high and left ventricular contractile function is impaired [23]. Such patients generally have recovery of left ventricular function after aortic valve replacement. Carabello, et al [24] studied the relationship between left ventricular ejection fraction and end-systolic wall stress in patients with aortic stenosis and impaired left ventricular systolic function (fig 2). The regression line indicates the normal relationship between ejection fraction and wall stress. Patients who fell along this line had recovery of left ventricular function post-operatively. The four subjects represented by x's manifested left ventricular dysfunction out of proportion to wall stress, suggesting intrinsically depressed contractility. Three of the four died perioperatively; the other continued to have NYHA Class IV heart failure. These four patients all had mean aortic pressure gradients of 25 mmHg or less; all of the other subjects had mean aortic gradients greater than 30 mmHg. *Thus, the mean pressure gradient in patients with severe aortic stenosis and left ventricular dysfunction may predict a poor outcome.*

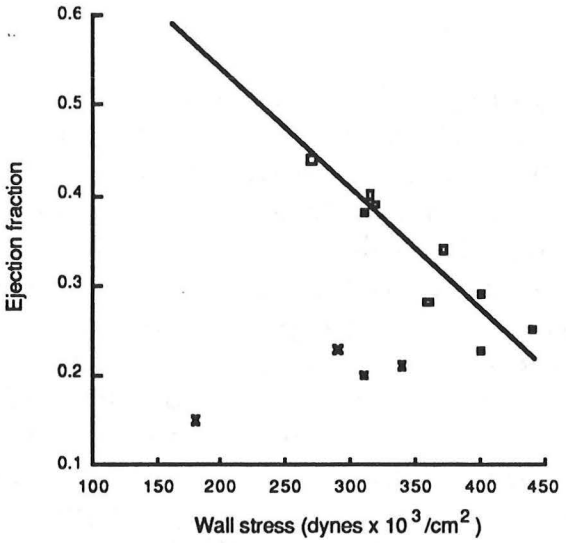


Figure 2. Plot of ejection fraction vs wall stress for AS pts with impaired LV systolic function (Carabello, et al)

Although left ventricular hypertrophy is a compensatory mechanism that normalizes wall stress and preserves left ventricular systolic function, it has adverse effects on left ventricular diastolic function [25-29]. Increased chamber stiffness and myocardial stiffness are important factors in causing dyspnea in patients with aortic stenosis due to elevated left ventricular filling pressures. Left ventricular filling becomes more dependent on atrial systole, causing a prominent a wave in the left atrial tracing. Thus, the loss of atrial "kick" during atrial fibrillation can provoke the rapid onset of pulmonary congestion with rapid clinical deterioration.

Left ventricular hypertrophy, increased intracavitary pressure, and prolongation of ejection combine to increase myocardial oxygen demand and reduce subendocardial perfusion. Accordingly, myocardial ischemia may occur even in the setting of normal coronary arteries. Marcus, et al [30] have shown that coronary flow reserve during pharmacologic hyperemia is impaired in aortic stenosis and may be partly responsible for angina in these patients.

Pressure Gradient

Catheterization. Pressure gradient across the aortic valve is directly measured at catheterization with simultaneous tracings from left ventricle and ascending aorta [31]. Typically, fluid-filled catheters interfaced to a strain-gauge transducer are employed. With proper balancing and calibration of the transducer, accurate pressure tracings are obtained, although artifacts due to catheter "whip" are not uncommon. To avoid such artifacts and to provide a superior frequency response, micromanometer-tipped catheters can be used instead. A dual-chip Millar catheter has two micromanometers such that left ventricular and aortic pressure can be recorded simultaneously with a single catheter across the aortic valve.

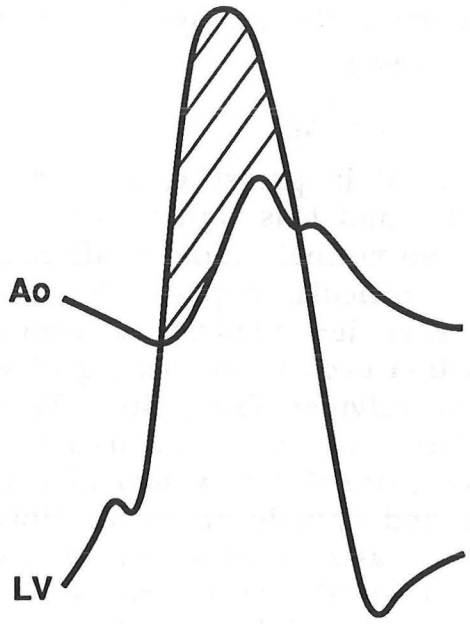


Fig 3. Simultaneous aortic and LV pressures. Mean gradient is determined by planimetry of the hatched area.

Although the aortic pressure gradient should be recorded simultaneously from the left ventricle and proximal aorta (fig 3), some laboratories measure the downstream pressure from the femoral artery sheath. This has been shown to underestimate the true gradient across the valve due to peripheral amplification of the pressure pulse [32], and is not an acceptable technique. Other laboratories employ a "pullback" technique wherein the left ventricular catheter is withdrawn to the proximal aorta and the pressure waveforms are then superimposed to determine the gradient. This also is prone to error and is not an accurate method of assessing the valve gradient [31].

Doppler ultrasound. When an ultrasound pulse of known frequency (f_o) encounters moving red blood cells, it is reflected back to the transducer at a different frequency. The difference between the transmitted and received frequency is called the frequency shift (f_d) and is determined by the velocity and direction of blood flow. This velocity can be calculated by the Doppler equation as [33]:

$$V = \frac{f_d \times c}{2f_o \cos \theta},$$

where c is the speed of ultrasound in body tissue (1540 m/s) and θ is the angle of incidence between the Doppler beam and blood flow (fig 3). Because the cosine of 20° is 0.94, velocity can be measured to within 6% so long as the angle of incidence is 20° or less. This is almost always possible with careful evaluation of blood flow from multiple transducer positions in experienced laboratories.

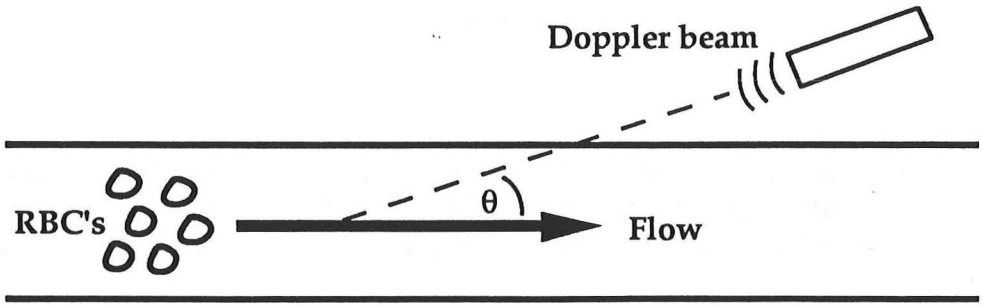


Fig 4. Angle of incidence (θ) between the Doppler beam and red blood cells (RBC's) moving at a given flow velocity.

The velocity of blood flow across the aortic valve can be converted to pressure gradient by application of the Bernoulli equation [33]. This equation relates pressure gradient (ΔP) to velocity as:

$$\Delta P = 2\rho\,(V_2^2 - V_1^2) + \rho\int \frac{dV}{dt}\,ds + R(V)$$

where ρ is the viscosity of blood, V_2 and V_1 are the velocities at the valve orifice and proximal to the valve, respectively. The second portion of the equation (integral of dV/dt ds) represents energy loss du to flow acceleration and R(V) represents energy loss due to viscous friction. By assuming that flow acceleration and viscous friction are negligible, and that V_1^2 is far less than V_2^2, the Bernoulli equation can be modified to:

$$\Delta P = 4\,V^2,$$

where V is the velocity at the valve orifice as measured by continuous wave Doppler. Note that Doppler ultrasound does not actually measure pressure gradient, but calculates it from the measured velocity using assumptions that may not be appropriate under low flow conditions. Nevertheless, a remarkably good correlation exists between mean pressure gradients determined by Doppler ultra-sound and cardiac catheterization [34-37]. For example, Currie, et al (fig 5) showed a close correlation in 100 consecutive patients studied with simultaneous Doppler and catheter measurements at the Mayo Clinic [34]. Unfortunately, pressure gradient does not adequately predict the severity of aortic valve stenosis, especially in low flow states. Therefore, aortic valve area calculation has become the "gold standard" for assessing the severity of aortic stenosis.

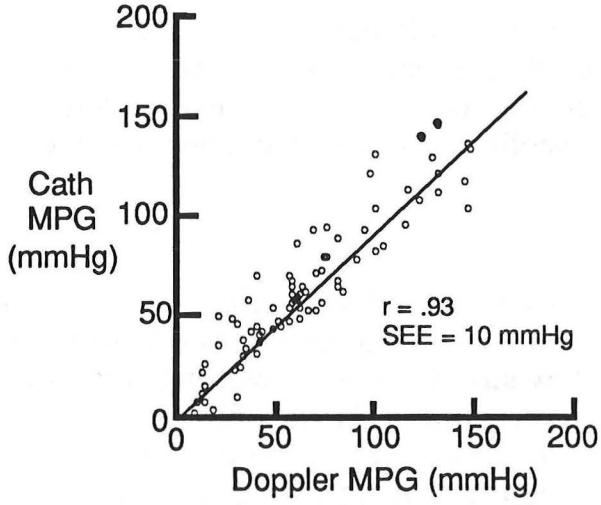


Fig 5. Comparison of mean gradient by catheter and Doppler ultrasound.

Aortic valve area calculation

Cardiac catheterization

In 1951, Gorlin and Gorlin [38] published the hydraulic orifice equation which subsequently became the "gold standard" for calculating aortic valve area. In fluid mechanics, area (A) is determined by flow (F) and velocity (V) according the equation:

$$F = A\,V$$

Accoding to this equation A is the area of the flow stream, which is slightly smaller than the orifice area (A_o) due to contraction of flow by viscous friction as it traverses the orifice. The contraction coefficient (c_c) accounts for this diffence such that:

$$F = c_c\,A_o\,V.$$

It is important to note that pressure gradient is not a primary determinant of valve area according to this equation. This is because pressure gradient represents the potential energy driving flow across the orifice. However, it is the kinetic energy, manifested as velocity, that along with flow determines orifice area. In 1951, Gorlin could measure flow (cardiac output) but had no method for measuring flow velocity. Thus, Gorlin proposed that V could be calculated from the pressure gradient by Torricelli's Law which states that:

$$V = c_v\sqrt{2gh},$$

where g is gravity acceleration, h is the mean pressure gradient, and c_v is a constant that accounts for the fact that some of the pressure gradient is not converted to velocity but is dissipated by viscous friction, turbulence, or inertial losses. By combining the two equations, valve area could be determined as:

$$A_o = \frac{F}{44.3\,C\sqrt{MPG}},$$

where 44.3 is equal to $\sqrt{2g}$, C is a constant combining c_c,c_v, and conversion from mmHg to cm, and MPG is the mean pressure gradient across the valve. Systolic flow across the aortic valve is determined from cardiac output, heart rate, and the systolic ejection period, such that the Gorlin formula for aortic valve area is;

$$AVA = \frac{CO \div (HR \times SEP)}{44.3\sqrt{MPG}}.$$

Note that the Gorlin formula for aortic valve area assumes that C = 1.0, i.e., that there are no energy losses due to friction, inertia, turbulence, and contraction of the flow stream (after converting from mmHg to cm H_2O). Moreover, the constant was never empirically determined for aortic stenosis because left heart catheterization to determine aortic pressure gradient had not yet been performed in 1951. Gorlin did compare calculated mitral valve areas with those estimated during surgery by palpation in 11 patients and empirically determine that for mitral stenosis, C = 0.85.

Limitations of the Gorlin formula. The Gorlin formula was derived from steady flow equations and its major limitation involves the empiric constant. In aortic stenosis, the assumption that pressure energy is completely converted to velocity cannot be correct. However, under the circumstance of high pressure gradients across a rigid valve, energy losses are probably negligible, and the Gorlin formula accurate. In low flow states, where the pressure gradient is low, the Gorlin equation is inaccurate and tends to underestimate valve area [39-40]. The Gorlin constant has also been shown to be dependent on orifice geometry [40,41], and is inaccurate if significant pressure energy is required to open the valve leaflets resulting in inertial losses not accounted for by the constant [42].

There are potential sources of error in measuring pressure gradient across the aortic valve. As noted previously, the use of femoral artery or "pullback" pressures is not acceptable. Carabello, et al [43] noted that in patients with very severe aortic stenosis, the presence of the catheter in the valve orifice increased the pressure gradient across the valve. This, however; should not result in a significant clinical error. More importantly, the phenomenon of pressure recovery could lead to underestimation of the true gradient by catheterization [44-47]. An example of pressure recovery is shown in figure 6. Under ideal conditions, as a flow stream converges to pass through a narrowed orifice, pressure energy is converted to velocity to maintain flow. As the stream exits the narrowed orifice and re-expands, velocity slows and pressure is recovered downstream. The pressure drop corresponding to the maximal velocity occurs at the vena contracta, which is the narrowest part of the flow stream. Failure to measure the pressure at this location may result in underestimation of the gradient. In the clinical setting, pressure recovery is limited by loss of pressure due to turbulent eddies and compliance of the ascending aorta. Pressure recovery is also greatly influenced by the geometry of the orifice, being greater with nozzle like orifices or slit-like orifices [48].

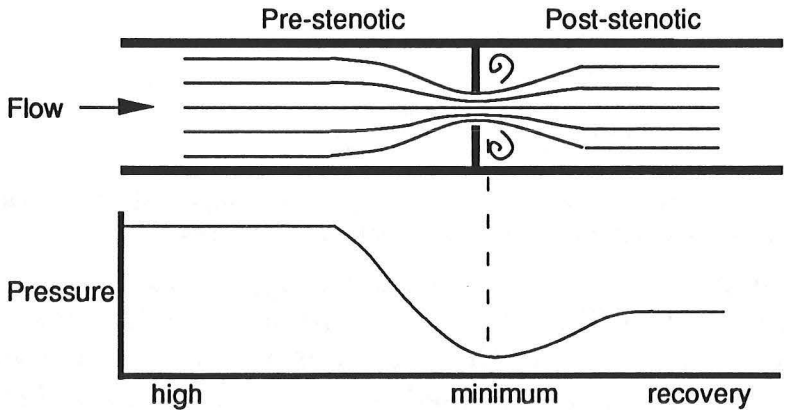


Fig 6. Pressure recovery downstream from a stenosis. Dashed line shows that the minimum pressure (highest gradient) occurs at the narrowest point of the flow stream (vena contracta).

Cardiac output determination may also influence the accuracy of the Gorlin formula. The Fick method is probably the most accurate in patients with low flow states [30]. Dye dilution methods are not accurate in patients with mitral or aortic

regurgitation [48]. In patients with significant tricuspid regurgitation, thermodilution technique underestimates cardiac output [50]. Finally, many patients have concomitant aortic stenosis and regurgitation. In such patients, flow across the aortic valve includes the forward flow (determined by Fick, dye dilution, or thermodilution) plus regurgitant flow [31]. Thus, angiographic cardiac output determined from the left ventricular stroke volume is theoretically more accurate than forward flow because the latter will underestimate valve area. Unfortunately, angiographic cardiac outputs are often inaccurate [31,51].

Despite the numerous limitations of the Gorlin formula, it has been used clinically for decades. Moreover, the Gorlin formula has been very important in demonstrating that pressure gradient alone does not determine the severity of aortic stenosis, but must be considered along with the amount of flow across the valve.

Doppler Echocardiography

Continuity equation. Flow equals area times velocity (F=AV). The continuity equation is derived from the principle of conservation of mass and states that flow is constant as it enters or emerges from a stenosis. Figure 7 schematically illustrates flow in a cylindrical tube entering a stenosis. According to the continuity equation, flow proximal to the stenosis (A_{prox} V_{prox}) equals flow at the stenosis (A_{sten} V_{sten}). Rearranging this equation, we can solve for the area of the stenosis as:

$$A_{sten} = \frac{A_{prox}\, V_{prox}}{V_{sten}}.$$

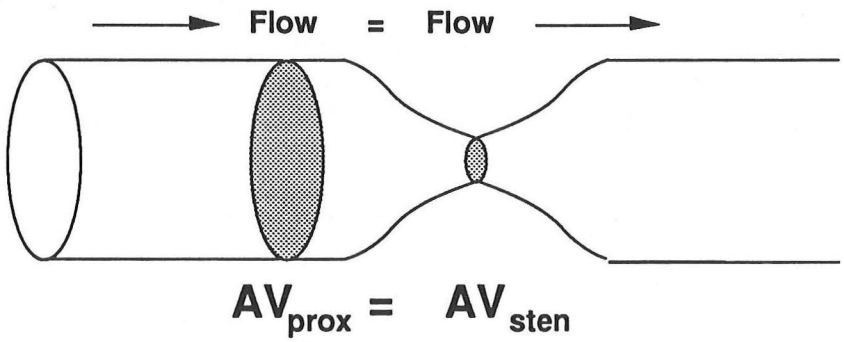


Fig 7. The continuity equation. Flow is equal at all points along the stream, such that velocity across the stenosis increases as cross-sectional area decreases.

For clinical assessment of aortic valve area, A_{prox} and V_{prox} are determined from the left ventricular outflow tract just proximal to the aortic valve. The diameter of the left ventricular outflow tract is measured by two-dimensional echocardiography, and area is determined as $\pi\, r^2$. Left ventricular outflow tract velocity (V_{prox}) is measured by pulsed Doppler, which is used to assess velocities at specific locations in the heart. The velocity across the aortic valve (V_{sten}) is determined by continuous wave Doppler. The Doppler technician must sample the velocities across the aortic valve from multiple sites, including the apex, suprasternal notch, and right parasternal border in order to obtain the best quality signal with the highest velocity (lowest angle θ).

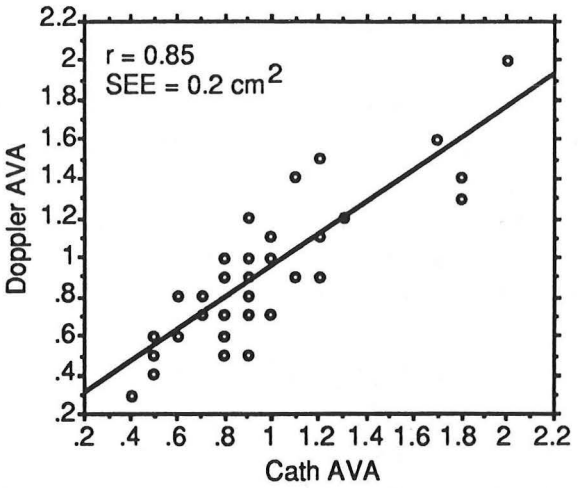


Fig 8. Comparison of aortic valve area by the continuity equation and catheterization.

It is important to note that the continuity equation and the Gorlin equation are identical mathematically. The denominator (V_{sten}) is measured by the Doppler method and calculated at catheterization from the pressure gradient and an empiric constant. Thus, it should not be surprising that Doppler echocardiography and catheterization correlate closely in aortic valve area calculation [52-58]. Figure 8 shows the Dallas VAMC data from 50 consecutive patients (some points overlap) undergoing assessment of aortic valve area by both Doppler and catheterization. The standard error of the estimate is consistently 0.2 cm^2 (95% confidence-0.4 cm^2) from study to study. Thus, 5% of the time, one can expect a significant difference in aortic valve area between Doppler and catheterization. Careful consideration of the clinical history, examination, and technical factors related to the Doppler study or catheterization can usually resolve the discrepancy.

Strengths of Doppler echocardiography. There are several advantages to the continuity equation. It is noninvasive and therefore suitable for serial studies. Theoretically, the continuity equation is superior to the Gorlin formula because 1) it measures velocity rather than pressure gradient, and 2) it contains no empiric constant. *Thus, the continuity equation should be more accurate than the Gorlin equation in low flow states.* Finally, measurement of flow in the left ventricular outflow tract renders this method accurate even in the setting of significant aortic regurgitation [59].

Limitations of Doppler echocardiography. Obesity, chronic lung disease, and chest wall configuration result in technically inadequate echocardiograms in 5-10% of patients. In addition, the Doppler technique is dependent on highly trained, experienced technicians. Failure to properly align the Doppler beam with the stenotic jet will underestimate the velocity. Inadequate imaging of the left ventricular outflow tract may result in errors in area determination. This problem is the most important source of error in the continuity equation because any error in measuring the outflow tract radius is squared. Finally, an inexperienced operator may mistake the velocity signal from mitral or tricuspid regurgitation for the aortic stenosis jet. Because of these technical limitations, it is imperative that all echocardiography laboratories prospectively validate their accuracy against catheterization before recommending valve surgery on the basis of their Doppler data alone. However, the data from high volume experienced laboratories demonstrate consistently high correlations with cardiac catheterization.

The Concept of Critical Aortic Stenosis

Opinions vary as to what constitutes "critical" aortic stenosis. The most widely used definition is 0.75 cm^2 (neither cath nor Doppler is accurate to 0.01 cm^2), however, several definitions can be found ranging from 0.5 to 1.0 cm^2 [60-66]. Virtually none of these sources reference any studies supporting their position and the few papers that are referenced contain no data. However, I believe that several considerations can lead to an appropriate concept of critical aortic stenosis.

Indexing for Body Size. Normal cardiac output values vary according to body surface area. Thus, a 1.0 cm^2 aortic valve might cause significant flow reduction and exertional dyspnea in a 100 kg man but result in no functional impairment in a 50 kg woman. Again, sources vary as to whether critical aortic stenosis should be defined as an indexed valve area $\leq$ 0.4 cm^2/m^2 or $\leq$ 0.6 cm^2/m^2. Tobin, et al [67] showed a reduction in left ventricular stroke work of $\geq$ 30% in patients in whom aortic valve area was $\leq$ 0.6 cm^2/m^2. Moreover, the natural history study of Chizner, et al [16] included 10 unoperated symptomatic patients with valve areas between 0.7 and 1.0 cm^2, considered "moderate" aortic stenosis by some definitions. Six of these ten died at an average of 9 months after catheterization. Similar data have been published by Kennedy, et al [68] who studied 66 patients with aortic valve areas between 0.7 and 1.2 cm^2 at catheterization. All but 12 were symptomatic; none were operated on because they were felt to have "moderate" aortic stenosis. The mortality at a mean of 35 months was 21%, an additional 32% went on to have valve replacement. The risk ratio was higher for those with indexed aortic valve areas $\leq$ 0.5 cm^2. *Thus, many patients with "moderate" aortic stenosis, defined as valve areas of 0.8 to 1.2 cm^2, have a poor prognosis and would be considered to have critical aortic stenosis if valve area were indexed for body surface area.*

Reproducibility of Measurement. The concept of critical aortic stenosis implies that measurements of aortic valve area by catheterization and by Doppler ultrasound are sufficiently accurate and reproducible to distinguish small differences in valve area. The standard error of the estimate for repeated assessment of aortic valve area by Doppler ultrasound on the same patients at different institutions is 0.2 cm^2 [69]. Similar data were recently presented for catheterization measurements of aortic valve area at initial study and at balloon valvuloplasty a few days later [unpublished data, Rahimtoola SH]. There are two reasons for differences in measurement of aortic valve area from day-to-day using the same technique. First, both catheterization and Doppler echocardiography have several potential limitations as discussed previously. Second, aortic valve area is not fixed, but may vary with changes in flow, particularly during low flow states [70]. Accordingly, Bache et al [71] exercised patients with aortic stenosis during cardiac catheterization and shown that calculated aortic valve area increased as cardiac output increased. Given the variability in calculating aortic valve area by either catheterization or Doppler techniques, one must consider that a valve area reported to be just outside the arbitrary value for critical aortic stenosis may in fact be critical aortic stenosis.

Surgical results. The surgical mortality for aortic valve replacement in aortic stenosis ranges from 2-8% and averages about 5% [60-63]. Successful surgery results in relief of symptoms, improvement in left ventricular function, regression of left ventricular hypertrophy, and 5-year actuarial survival rates of 85% [60-63]. However, the mean aortic valve area post-operatively in a large VA cooperative study was 1.4 ± 0.5 cm^2 [72]. The expected improvement in aortic valve area with surgery depends on the type and size of the implanted valve prosthesis. Table I summarizes data from several sources [73-76] regarding expected aortic prosthetic valve areas. The decision to replace the aortic valve in a given patient must take into account the size and the type of prosthesis to be implanted. Aortic balloon valvuloplasty results in a mean valve area of 0.9 cm^2 [63], and has six-month restenosis rates of approximately 75%. Therefore, balloon valvuloplasty for aortic stenosis is recommended only for patients in whom valve replacement is considered too risky.

Table I. Expected valve areas for different aortic prosthetic valves.

	Post-Operative Aortic Valve Area (cm^2)			
Valve Type	19 mm	21 mm	23 mm	25 mm
bioprosthesis	0.9 ± 0.2	1.1 ± 0.3	1.6 ± 0.6	1.7 ± 0.5
tilting disc	1.0 ± 0.4	1.4 ± 0.2	1.7 ± 0.5	2.4 ± 0.7
bileaflet	1.4 ± 0.2	1.6 ± 0.2	2.3 ± 0.4	2.6 ± 0.2

Symptoms. Traditionally, asymptomatic patients did not get referred to the catheterization laboratory, so there were few data regarding this issue. However, the advent of Doppler echocardiography as an accurate method of assessing aortic valve area has commonly identified asymptomatic individuals with critical aortic stenosis. Two large series have been published to date. Kelly, et al [77] followed 51 asymptomatic aortic stenosis patients with peak Doppler-derived gradients of ≥ 50 mmHg. During a mean follow-up period of 17 ± 9 months, 21 patients became symptomatic. Only 2 (3.9%) patients died, and in both cases death was preceded by the development of symptoms. Pellikka, et al [78] studied 143 asymptomatic patients, all of whom had a peak velocity of ≥ 4 m/s across the aortic valve by continuous wave Doppler. Valve replacement or balloon valvuloplasty was performed in 30 of these patients, leaving 113 asymptomatic patients with long-term follow-up. Over a mean follow-up of 20 months, 37 (33%) patients became symptomatic. Actuarial survival was 94% at one year, and 90% at two years, no different than age- and sex-matched controls. Only three deaths were attributed to aortic stenosis, and all of these developed symptoms at least three months before death. Thus, no patient who remained asymptomatic died of aortic stenosis in either series. This supports the traditional teaching that asymptomatic patients with critical aortic stenosis do not require surgery until symptoms develop [79]. *It should be clear from the above considerations that symptoms, rather than aortic valve area, are the primary predictor of the need for aortic valve replacement.*

New concepts in quantitating aortic stenosis. Hemodynamic resistance, defined as the mean gradient divided by the mean systolic flow rate has been proposed as an alternative to the Gorlin equation in assessing the severity of aortic stenosis [80]. This parameter is attractive because of its lack of an empiric constant. However, the continuity equation also lacks the empiric constant and calculates valve area, a value that is simple to understand and to compare with prosthetic valve areas. It remains to be determined whether valve resistance will become clinically useful.

Conclusions. Aortic valve replacement is indicated in patients with symptomatic, severe aortic stenosis (AVA $\leq$ 0.5 cm^2/m^2). The decision to operate can be made in most patients on the basis of symptoms, clinical findings, and Doppler assessment of aortic valve area. Most patients will still require cardiac catheterization to define coronary anatomy pre-operatively. In patients with high quality Doppler data, the physician performing the catheterization may omit right heart catheterization and placement of a catheter across the aortic valve to save time and minimize the risk of catheter-induced arrhythmias. In patients with poor quality Doppler studies, calculation of aortic valve area at catheterization remains necessary to determine the need for surgery. Asymptomatic patients with Doppler evidence of severe aortic stenosis should be followed carefully (every 3-4 mos) for development of symptoms.

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