Profiles in Valvular Heart Disease

William Grossman

The cardiac valves have as their function the maintenance of unidirectional flow, to ensure that the energy released during myocardial contraction is transformed efficiently into the circulation of blood around the body. When the valves become diseased, compensatory mechanisms are brought into play to maintain the circulation commensurate with the metabolic needs of the body. These mechanisms, chief among which are dilatation and hypertrophy, are not without clinical costs, and it is these costs that are responsible for the major manifestations of valvular heart disease.

Valvular disease results in either incompetence of the valve with regard to its function of maintaining unidirectional flow (i.e., valvular insufficiency and regurgitation) or obstruction to the forward and natural course of the circulation (i.e., stenosis). Although mixed stenosis and insufficiency, both of moderate degree, frequently coexist in a particular valve, severe stenosis and severe insufficiency are almost never both present in the same valve. For example, the 0.5-cm² valvular orifice of a patient with severe calcific aortic stenosis may barely allow 50 to 60 mL to be ejected from the left ventricle during systole, and this only at a left ventricular systolic pressure of 200 to 300 mm Hg. The tiny fixed orifice cannot be expected to permit more than mild regurgitation in the subsequent diastole, where the driving force is an aortic diastolic pressure of 80 mm Hg.

I have seen an exception to this general rule in a middle-aged woman with rheumatic aortic stenosis and insufficiency. Aortography demonstrated severe aortic regurgitation; nevertheless, there was a resting transaortic systolic gradient of approximately 60 mm Hg. The explanation was apparent on close examination of the aortic valve during cineaortography: Although two leaflets were heavily calcified and immobile, the third was thickened but mobile. During diastole this leaflet prolapsed freely into the left ventricular cavity, whereas during systole its opening motion was limited or checked by apparent abutment against the free edges of the other two calcific, immobile leaflets. Another example of mixed, severe stenosis and aortic insufficiency is described later in this chapter and illustrated in Fig. 29.9.

Valvular heart disease may be considered to impose two different types of stress on the cardiac chamber proximal to the lesion—either pressure overload (increased afterload) or volume overload (increased preload). The former is generally the result of valvular stenosis and the latter of valvular insufficiency. Both pressure overload and volume overload serve as stimuli for the heart to call on compensatory mechanisms. As mentioned, chief among these mechanisms are hypertrophy (which allows the generation of greater systolic force and at the same time tends to normalize wall stress by increasing wall thickness) and dilatation (which enables increased strength and extent of shortening by the Frank-Starling mechanism). These mechanisms preserve the circulation at the cost of increased myocardial oxygen needs and elevated ventricular filling pressures, leading to clinical evidence of ischemia and congestive heart failure.

This chapter illustrates the hemodynamic and angiographic findings seen in patients with valvular heart disease. It is useful to apply the general physiologic principles just discussed to the interpretation of catheterization data obtained from patients with disordered valve function, and this approach generally enables the physician to unravel even the most complicated problems.

MITRAL STENOSIS

The orifice area of the normal mitral valve is about 4.5 cm². As a result of chronic rheumatic heart disease, the orifice becomes progressively smaller, and this leads to at least two distinct and important circulatory changes (1). The first is the development of a pressure gradient across the mitral valve, the left ventricular mean diastolic pressure
remaining at its normal level of about 5 mm Hg and the left atrial mean pressure rising progressively, reaching about 25 mm Hg when the orifice of the mitral valve is reduced to approximately 1.0 cm$^2$ (Fig. 29.1). A second major circulatory change is reduction of blood flow across the mitral valve (i.e., reduction of the cardiac output). The normal resting cardiac output of 3.0 L/min/m$^2$ usually falls to about 2.5 L/min/m$^2$ when the valve size is 1.0 cm$^2$. A rise in left atrial pressure necessitates a similar rise in pressure in pulmonary veins and capillaries, and pulmonary edema occurs when the pulmonary capillary pressure exceeds the oncotic pressure of normal plasma, which is about 25 mm Hg.

**FIG. 29.1.**

Simultaneous left atrial (LA) and left ventricular (LV) pressures (A) and pulmonary capillary wedge (PCW) and LV pressures (B) in a patient with tight mitral stenosis and a mean PCW pressure of approximately 25 mm Hg. LV end-diastolic pressure is normal at 10 mm Hg. Note the presence of a waves in the LA and PCW trace which are not transmitted to the LV because of the damping effect of the stenotic mitral valve. (Reproduced from Lange RA, et al. Use of pulmonary capillary wedge pressure to assess severity of mitral stenosis: is true left atrial pressure needed in this condition? *J Am Coll Cardiol* 1989;13:825, with permission.)

Reactive pulmonary hypertension practically never occurs in mitral stenosis until the mitral valve area approaches 1.0 cm$^2$ (i.e., when the resting left atrial pressure approaches 25 mm Hg). After this point, reactive changes in the pulmonary arteriolar bed develop frequently, resulting in progressive obstruction to blood flow through the lungs.

As pulmonary vascular obstruction becomes increasingly severe, the pulmonary arterial pressure rises and occasionally may exceed the systemic arterial pressure. In the extreme, the pulmonary vascular resistance can rise to 25 or 30 times normal. Despite substantial hypertrophy, the right ventricle cannot cope with the enormous pressure load imposed on it, and it dilates and fails.

Thus, in mitral stenosis, two “stenoses” eventuate-first at the mitral valve and second in the arterioles of the lung. The hemodynamic findings in patients with tight mitral stenoses with and without major pulmonary vascular disease are illustrated in Fig. 29.2. As can be seen, the second stenosis (bottom panel) has resulted in a 70-mm Hg mean pressure gradient across the lungs, giving a pulmonary vascular resistance of 1866 dyn·sec·cm$^{-5}$. Workup of the patient with mitral stenosis should include an assessment of both of these obstructions.

**FIG. 29.2.**

Diagrammatic representation of the circulation in patients with normal hemodynamics (top), tight mitral stenosis (center), and tight mitral stenosis with pulmonary vascular disease and the development of a second stenosis at the pulmonary arteriolar level (below). (See text for discussion.)

**Catheterization Protocol**

The usual indication for cardiac catheterization in patients with mitral stenosis is that the patient is being considered for either balloon mitral valvuloplasty or corrective surgery. Catheterization should be a combined right- and left-sided heart procedure in which the following measurements and calculations are made:

1. Simultaneous left ventricular diastolic pressure, left atrial (or pulmonary capillary wedge) diastolic pressure, heart rate, diastolic filling period, and cardiac output. From these, the size of the mitral valve orifice may be calculated (see Chapter 10 for details of the orifice area calculation).
2. If the transmural pressure gradient is less than 5 mm Hg, the error in calculation of the mitral valve orifice area is appreciable. The circulatory measurements should be repeated under circumstances of stress (exercise, reversible increase in preload resulting from passive elevation of the patient's legs, tachycardia induced by pacing) to increase the pressure gradient across the mitral valve.
3. Simultaneously, or in close order, pulmonary arterial mean pressure, left atrial (or PCW) mean pressure, and
cardiac output for the calculation of pulmonary vascular resistance.

4. Right ventricular systolic and diastolic pressures for assessment of right ventricular function.

5. If other lesions are suspected (e.g., mitral regurgitation, aortic valve disease, left atrial myxoma), they too must be evaluated. Certain lesions tend to occur in combination with mitral stenosis. Many (if not most) patients with severe mitral stenosis have some degree of aortic regurgitation. Also, although it is rare, tricuspid stenosis always should be looked for in the patient with severe mitral stenosis, because it is seen only in association with this condition. Another condition that may be associated with mitral stenosis is atrial septal defect with left-to-right shunt. The combination of mitral stenosis and atrial septal defect is known as Lutembacher's syndrome. Therefore, as with standard right-sided heart catheterization, described in Chapters 4 through 6, the operator should obtain screening blood samples from the superior vena cava and pulmonary artery for oximetry determination. This has taken on added importance in the present era when balloon mitral valvuloplasty (see Chapter 26) has become a standard treatment for mitral stenosis. Balloon mitral valvuloplasty usually requires transseptal catheterization and involves limited dilatation of the interatrial septum; the procedure may create an atrial septal defect, thereby producing iatrogenic Lutembacher's syndrome (2).

The following case studies illustrate the clinical and hemodynamic syndromes seen in patients with mitral stenosis. The first is a typical example of a symptomatic patient with “tight” mitral stenosis, normal pulmonary vascular resistance, and a normal-sized heart (stage II in Fig. 29.3). The second is an example of a relatively asymptomatic patient with more severe mitral stenosis, a 5- to 10-fold increase of pulmonary vascular resistance, and an enlarged heart caused principally by enlargement of the right ventricle (stage III). The third represents terminal mitral stenosis with an extreme degree of pulmonary vascular resistance, pulmonary hypertension, and right ventricular failure (stage IV).

**FIG. 29.3.**

Stages in the natural history of mitral stenosis. As the mitral orifice progressively narrows, pulmonary vascular resistance increases. The increase is slow at first, but when the mitral valve area becomes “critical” (less than 1 cm\(^2\)), the increase is rapid, reflecting the development of a second stenosis at the level of the precapillary pulmonary arterioles. Clinical correlations are discussed in the text.

**Case 1: Tight Mitral Stenosis with Normal Pulmonary Vascular Resistance**

A.R., a 35-year-old woman, had chorea as a child and was asymptomatic thereafter until age 33 years, when she noted the onset of exertional dyspnea. This progressed to the point of her having to stop after climbing one flight of stairs slowly. She had had one recent episode of hemoptysis. Her most troublesome symptom at the time of presentation had been paroxysmal atrial fibrillation over a period of several months. She had had orthopnea and one episode of paroxysmal nocturnal dyspnea.

On physical examination, she was in no apparent distress. Blood pressure was 130/70 mm Hg, and pulse rate was 80 beats per minute (bpm) and regular. There was no jugular venous distention, the lungs were normal, and the point of maximal impulse was in the fifth interspace in the midclavicular line. The first heart sound (S1) was accentuated. At the apex, there was a grade 1/6 holosystolic murmur, an opening snap, and a grade 2 diastolic rumble with presystolic accentuation. The liver edge was at the costal margin, and there was no edema. The electrocardiogram (ECG) was within normal limits. The chest roentgenogram showed a normal-sized heart, an enlarged left atrium, a mild degree of pulmonary vascular redistribution, and no calcification in the region of the mitral valve, and was otherwise normal.

Cardiac catheterization revealed the following:

Cineangiography of the left ventricle revealed no mitral regurgitation.

**Interpretation**
This patient was symptomatic because of her increased left atrial pressure and atrial arrhythmia. She had not yet developed the “second stenosis” at the precapillary pulmonary arteriolar level discussed previously. Therefore her pulmonary artery pressure elevation was purely a consequence of the increased left atrial and pulmonary venous pressures, and the pulmonary vascular resistance was normal (less than 120 dyn·sec·cm⁻⁵). In the spectrum of patients with mitral stenosis, she would fall into stage II (Fig. 29.3). Appropriate therapy might be balloon mitral valvuloplasty or surgical mitral commissurotomy. Without relief of the mitral stenosis, her paroxysmal atrial fibrillation is likely to become continuous.

Case 2: Severe Mitral Stenosis, Moderately Elevated Pulmonary Vascular Resistance, Few Symptoms, Fatigue Syndrome

E.C., a 42-year-old woman, had no history of acute rheumatic fever. She was asymptomatic until she was 19 years old, when, during the last month of her first pregnancy, at which time she was quite anemic, she developed pulmonary congestion. She responded well to therapy and remained asymptomatic thereafter, even during three subsequent pregnancies. However, during her fifth pregnancy at age 37 years, dyspnea, orthopnea, paroxysmal nocturnal dyspnea, and one episode of hemoptysis of pure red blood occurred at the seventh month, necessitating hospitalization through term. Thereafter she improved but became progressively tired with loss of energy and drive. She became less thorough in her housework and in her attention to the children's clothes and lost her previous meticulousness. If she pushed herself, she would become somewhat short of breath on a flight of stairs, but it was fatigue more than breathlessness that bothered her.

On examination, she was well nourished and had a malar flush. Her blood pressure was 115/70 mm Hg; her pulse was 90 bpm and irregularly irregular. Respirations were 15 per minute. There was no pulmonary or peripheral congestion. The neck veins were just visible at the clavicles with the patient sitting upright. The point of maximal impulse was in the fifth interspace just outside the midclavicular line. The impulse was normal. A prominent parasternal heave was present. S1 was accentuated. No apical systolic murmur was present. There was an opening snap and a grade 2 apical diastolic rumble. The ECG showed right ventricular hypertrophy and atrial fibrillation. Chest radiographs showed the heart to be moderately enlarged because of enlargement of the left atrium and right ventricle. The pulmonary arteries were prominent, and there was a moderate degree of pulmonary vascular redistribution.

The findings at cardiac catheterization were as follows:

Interpretation

This patient's symptoms were caused initially by elevated left atrial pressure when, during her fifth pregnancy, she developed hemoptysis, orthopnea, and paroxysmal nocturnal dyspnea. Subsequently, however, her major symptom was fatigue, associated with a reduced cardiac output and an increased arteriovenous oxygen difference (A-V O₂ difference). The orthopnea and paroxysmal dyspnea had receded somewhat despite the fact that her pulmonary capillary pressure was at the pulmonary edema level. This is a common, although poorly understood, phenomenon in patients with mitral stenosis when pulmonary vascular disease begins to occur. Therefore, this patient was beginning to develop the “second stenosis” discussed previously, and this is apparent from the elevated pulmonary vascular resistance (520 dyn·sec·cm⁻⁵). In the spectrum of patients with mitral stenosis, she would be representative of stage III (Fig. 29.3). As was true for the patient in case 1, appropriate therapy would be either balloon mitral valvuloplasty or surgical commissurotomy.

Case 3: Terminal Mitral Stenosis with Severe Pulmonary Hypertension

C.A., a 47-year-old woman, had had acute rheumatic fever at 8 years of age and a murmur ever since. She did well until age 42 years, when she noticed exertional dyspnea and paroxysmal nocturnal dyspnea. At age 43, these symptoms worsened. Orthopnea and ankle edema appeared. Her symptoms then improved for almost 2 years, only to return 2 months before admission. Since then, despite a good cardiac regimen, she had had to lead a bed-chair-bathroom existence.
On examination, she was cachectic, dyspneic, and orthopneic. Acrocyanosis was evident. Blood pressure was 96/72 mm Hg; pulse rate was 90 bpm and irregularly irregular; respirations were 32 per minute. Neck veins were distended to the angle of the jaw, waves were prominent, and there were bibasilar rales over the lung fields. The point of maximal impulse was in the anterior axillary line. The apex impulse was normal, but a parasternal heave was present. S1 was loud. Systole was silent. An opening snap was present, and there was a barely audible mitral diastolic murmur with appreciable presystolic accentuation. The pulmonary component of S2 was loud. The liver was palpable, two fingerbreadths below the right costal margin and was tender. There was considerable pitting edema to the knees. The ECG showed atrial fibrillation, right-axis deviation, and right ventricular hypertrophy. Chest roentgenogram showed a large heart with prominent left atrium, right ventricle, pulmonary arteries, pulmonary vasculature, and Kerley B lines.

Cardiac catheterization revealed the following:

Interpretation

This patient had symptoms of left atrial hypertension 5 years before her catheterization, suggesting that she was in stage II (Fig. 29.3) of mitral stenosis at that time. At the time of presentation to us, she had evidence of advanced right-sided heart failure and pulmonary hypertension. This woman had “two stenoses,” and both were severe: The mitral orifice area was less than one-tenth normal at 0.3 cm², and the pulmonary vascular resistance was approximately 18 times normal at 1838 dyn·sec·cm⁻⁵. She was in late stage IV of mitral stenosis (Fig. 29.3). Even at this stage in their course, patients can respond dramatically to correction of their mitral stenosis. As pointed out in Chapter 8, pulmonary vascular resistance gradually returns toward normal in patients with advanced mitral stenosis (stage III or IV) after successful balloon valvuloplasty or surgical commissurotomy/valve replacement.

MITRAL REGURGITATION

Mitral incompetence, failure of the valve to prevent regurgitation of blood from the left ventricle to the left atrium during ventricular systole, may be caused by functional or anatomic inadequacy of any one of the components of the mitral valve apparatus, which consists of two valve leaflets, two papillary muscles with their chordae tendineae, and the valve ring or annulus.

Mitral regurgitation may occur when there is destruction or deformation of the valve leaflets as a result of rheumatic fever or bacterial endocarditis. In patients with mitral regurgitation resulting from either of these conditions, mitral regurgitation begins during “isometric” ventricular contraction and continues throughout systole, giving rise to a holosystolic murmur. A fibromyxomatous process in the mitral valve leaflets and chordae tendineae may give rise to mitral prolapse and the “floppy valve syndrome.” In such patients, regurgitation usually does not begin until ventricular ejection has led to a reduction in left ventricular chamber size, so that the regurgitation and accompanying murmur occur in middle or late systole. There may or may not be evidence of Marfan's syndrome in these patients. The papillary muscles are usually normal, but there is a marked redundancy of the valve leaflets and chordae with resulting prolapse into the left atrium during systole and accompanying regurgitation.

The papillary muscles are particularly vulnerable to ischemia from coronary artery disease and damage from viral myocarditis. The posterior papillary muscle derives its blood supply from the right coronary and left circumflex arteries. Ischemic dysfunction of this muscle may occur in association with either an inferior or posterolateral myocardial infarction. Less frequently, ischemic involvement of the anterior papillary muscle in an anterior or anterolateral infarction produces mitral regurgitation. Papillary-chordal integrity is maintained to a point when the left ventricle dilates. The common occurrence of a mitral regurgitant murmur in patients with large left ventricles, however, may reflect a simple anatomic loss of this integrity, an involvement of the papillary muscle with the same disease that causes the left ventricle to dilate, or an abnormality of contraction of the mitral annulus.

Physiology
Mitral regurgitation from whatever cause implies a double outlet to the left ventricle: During systole, blood exits the left ventricle through both aortic and mitral valves. Although total left ventricular output rises, that going into the aorta may fall. The left ventricular “output” regurgitated through the mitral valve depends on at least five factors: the size of the regurgitant orifice, left atrial compliance, the systolic mean pressure difference between the left ventricle and the left atrium, the duration of systole, and the resistance to forward ejection of blood through the aortic valve and into the aorta (e.g., aortic stenosis or peripheral vasoconstriction exacerbates mitral regurgitation). Although hypertension aggravates and lowering of blood pressure lessens mitral regurgitation, the most important factor is probably the size of the regurgitant orifice.

In patients with mitral regurgitation, cardiac catheterization is important to provide a complete hemodynamic and angiographic assessment of the severity of the valvular lesion.

**Hemodynamic Assessment**

First, it is important to assess the hemodynamic consequences of the mitral regurgitation by measuring cardiac output and right and left heart pressures (3–8).

**Interpretation of V Waves in the Pulmonary Capillary Wedge Tracing**

With acute mitral regurgitation (e.g., ruptured chordae tendineae), giant \( v \) waves are seen in the left atrial or pulmonary artery pressure tracing (Fig. 29.4). In this regard, our Fellows and Residents have often asked, “How large must a \( v \) wave be in order to be diagnostic of severe mitral regurgitation?” In my experience, \( v \) waves up to twice the mean left atrial pressure can be seen in the absence of any mitral regurgitation. The patient with left ventricular failure from any cause may have a distended, noncompliant left atrium, and the normal \( v \) wave (which is caused by left atrial filling from the pulmonary veins during left ventricular systole) will be prominent in this circumstance (7). When pulmonary blood flow is increased, the normal \( v \) wave increases in prominence correspondingly; this is particularly striking in cases of acute ventricular septal defect complicating myocardial infarction, in which enormous \( v \) waves (more than 50 mm Hg) can be seen in the absence of any mitral regurgitation.

**FIG. 29.4.**

Left ventricular (LV) and pulmonary capillary wedge (PC) pressure tracings from a patient with ruptured chordae tendineae and acute mitral insufficiency. The giant \( v \) wave results from regurgitation of blood into a relatively small and noncompliant left atrium. The electrocardiogram (ECG) tracing illustrates the timing of the PC \( v \) wave; its peak follows ventricular repolarization, as manifested by the T wave of the ECG.

\( V \) waves greater than twice the mean left atrial (or PCW) pressure are suggestive of severe mitral regurgitation, and when the height of the \( v \) wave is three times higher, a diagnosis of severe mitral regurgitation is virtually certain (Fig. 29.4). However, the absence of a prominent \( v \) wave by no means rules out severe mitral regurgitation. Slowly developing chronic mitral regurgitation commonly leads to marked left atrial enlargement, and the dilated left atrium can accept an enormous regurgitant volume per beat without any increase in mean pressure or height of the \( v \) wave (9). Also, the level of afterload, as determined by systemic vascular resistance, may greatly affect the height of the regurgitantor \( v \) wave in patients with mitral regurgitation (4). As seen in Fig. 29.5, a patient with severe mitral regurgitation had a \( v \) wave of 48 mm Hg at a time when left ventricular systolic pressure was approximately 140 mm Hg. With sodium nitroprusside (right-hand panel), the left ventricular systolic pressure came down to 120 mm Hg, and the \( v \) wave was essentially abolished (10). Although this patient's regurgitant fraction was reduced with sodium nitroprusside (from 80% to 64%), it still remained in the range of severemitral regurgitation (see later discussion). Assummarized in a study by Snyder et al. (11), prominent \( v \) waves in the PCW tracing are insensitive and have a poor positive predictive value for identifying moderate or severe mitral regurgitation.

**FIG. 29.5.**
Left ventricular and pulmonary capillary wedge pressures before (left) and during (right) an infusion of sodium nitroprusside in a patient with severe mitral regurgitation and atrial fibrillation. These tracings illustrate the sensitivity of the \( v \) wave height to left ventricular afterload in patients with mitral regurgitation. (See text for discussion.) (From Harshaw CW, et al. Reduced systemic vascular resistance as therapy for severe mitral regurgitation of valvular origin. Ann Intern Med 1975;83:312.)

**Exercise Hemodynamics**

Another important hemodynamic parameter in the assessment of mitral regurgitation is the forward cardiac output. Low cardiac output is common in advanced mitral regurgitation and may account for much of the clinical picture. If resting cardiac output is near normal, and if the patient's primary symptoms are related to exertion (i.e., easy fatigability and dyspnea on exertion), dynamic exercise during cardiac catheterization may be revealing. If the symptoms are cardiac in origin, the patient usually fails to increase cardiac output appropriately with exercise; that is, the increase in cardiac output is less than 80% of predicted (see formula for prediction of cardiac output increase with exercise in Chapter 15). In addition, PCW or left atrial mean pressure rises with exercise, commonly reaching levels greater than 35 mm Hg by 4 to 5 minutes of supine bicycle exercise, even if the control value was almost normal.

**Angiographic Assessment**

The second objective of cardiac catheterization in patients with mitral regurgitation is the angiographic assessment of the severity of the regurgitation by left ventriculography. The assessment may be qualitative, by noting the degree of opacification of the left atrium caused by regurgitation back through the incompetent valve, using a scale of 1+ (mild), 2+ (moderate), 3+ (moderately severe), and 4+ (severe) regurgitation. Although these grades are subjective, certain criteria can be used to enhance consistency of their use. Regurgitation that is 1+essentially clears with each beat and never opacifies the entire left atrium. When regurgitation is 2+ (moderate), it does not clear with one beat and generally does opacify the entire left atrium (albeit faintly) after several beats; however, opacification of the left atrium does not equal that of the left ventricle. In 3+ regurgitation (moderately severe), the left atrium is completely opacified and achieves equal opacification with the left ventricle. In 4+ regurgitation (severe), opacification of the entire left atrium occurs within one beat, opacification becomes progressively more dense with each beat, and contrast material can be seen refluxing into the pulmonary veins during left ventricular systole.

**Regurgitant Fraction**

The angiographic assessment of severity of mitral regurgitation also may be made more quantitative by calculation of the regurgitant fraction. This entails measurement of total left ventricular stroke volume (TSV) from the left ventriculogram and the amount that goes forward by way of the aorta to the body (the forward stroke volume, FSV) by Fick or indicator-dilution technique. The TSV is calculated as the difference between end-diastolic and end-systolic left ventricular volumes (EDV - ESV = TSV), as described in Chapter 16. Regurgitant stroke volume (RSV, regurgitant volume per beat) is given as RSV = TSV - FSV. Regurgitant fraction (RF) is then calculated as RF = RSV/TSV.

The accuracy of these calculations depend son many factors. Because FSV is calculated by dividing the cardiac output by the heart rate at the time of Fick (or other) cardiac output determination, it is an average stroke volume. The particular beat chosen from the left ventriculogram for volume determination must therefore be an “average” or representative beat; alternatively, volumes from multiple beats may be calculated and averaged. In patients with atrial fibrillation or extra systoles during ventriculography, the regurgitant stroke volume and regurgitant fraction may be highly inaccurate, and they should not be calculated in such patients. It also should be obvious that the accuracy of the regurgitant fraction depends on a similar physiologic state's prevailing between the cardiac output and angiographic phases of the catheterization procedure. An increase in arterial blood pressure may substantially increase the mitral regurgitation and decrease forward output. Therefore, if blood pressure or other hemodynamic variables change significantly between the time of cardiac output determination and left ventriculography, it is pointless to calculate regurgitant fraction. Finally, the regurgitant fraction quantifies, at best, the total amount of regurgitation. Therefore, if a patient has both mitral and aortic regurgitation, the regurgitant fraction gives an assessment of the regurgitation resulting from both lesions combined.
A study from the Mayo Clinic used left ventricular cineangiography to calibrate Doppler echocardiographic techniques for quantification of mitral regurgitation in 180 patients with isolated, pure mitral regurgitation (12). Patients had left ventricular cineangiography to quantify mitral regurgitation, using a grading scale of I to IV, much as just described. The researchers found that grade I angiographic mitral regurgitation corresponded to a Doppler-measured regurgitant fraction of 28% ± 9%, grade II to 38% ± 9%, grade III to 44% ± 10%, and grade IV to 59% ± 12%. The finding for grade I is surprising and probably reflects the sensitivity of the Doppler technique in detecting mitral regurgitation. Using angiographic methods for quantifying left ventricular volumes and regurgitant fraction, grade I (mild) angiographic mitral regurgitation probably corresponds to a regurgitant fraction of less than 20%, grade II (moderate) to 20% to 40%, grade III (moderately severe) to 41% to 60%, and grade IV (severe) to more than 60%.

Assessment of Left Ventricular Function

A third objective of cardiac catheterization in patients with mitral regurgitation is the assessment of left ventricular function by measurement of the left ventricular diastolic pressure and, more importantly, the left ventricular ejection fraction (LVEF) and end-systolic volume. As others have emphasized, the nearer the preoperative ejection fraction is to normal, the greater is the degree of postoperative restoration to full activity. Specific parameters of left ventricular function are discussed in Chapters 16 and 17.

Catheterization Protocol

1. Right-sided heart catheterization for evaluation of right atrial pressure (to detect possible tricuspid valve disease or right ventricular failure), pulmonary artery pressure (degree of pulmonary hypertension), and PCW pressure (v wave height). In severe, acute mitral regurgitation, a v wave may actually be seen in the pulmonary artery as a second or late systolic hump in the pressure waveform (8).
2. Left-sided heart catheterization for measurement of left ventricular end-diastolic pressure (LVEDP) and assessment of gradients (if any) across mitral or aortic valves. A characteristic of severe mitral regurgitation is that the LVEDP is usually much lower than the left atrial or PCW mean pressure. In contrast, in left ventricular failure due to cardiomyopathy or coronary artery disease, LVEDP is usually equal or approximately equal to the PCW mean pressure, and in aortic regurgitation or left ventricular aneurysm, LVEDP is usually much higher than the PCW mean pressure.
3. Cardiac output by Fick or indicator-dilution technique. This measures the fraction of blood going out by way of the aorta to the body and by itself yields no information about regurgitant flow. The response of forward cardiac output to dynamic exercise may provide useful information, however, because patients with severe mitral regurgitation are usually incapable of increasing forward output commensurate with the needs of the body, as estimated by the increased oxygen consumption (see Chapter 15).
4. Left ventriculography is the definitive method for evaluating mitral regurgitation. By this method, it is possible to measure left ventricular volumes and regurgitant fraction, as discussed previously. Coronary angiography usually is carried out as well, to assess the need for revascularization at the time of valve repair or replacement surgery, should that prove necessary.
5. Pharmacologic intervention. An infusion of sodium nitroprusside (Fig. 29.5) often has a dramatic and salutary effect on the hemodynamic abnormalities in mitral regurgitation and may have both diagnostic and therapeutic value. Although TSV may not change, RSV decreases and FSV increases, leading to increased cardiac output.

Case 4: Mitral Regurgitation

G.A. was a 59-year-old woman with no history of rheumatic fever in childhood. She was healthy and active until 6 months before admission, when she noticed both dyspnea and lower chest discomfort on mild exertion but no other symptoms of heart failure. There was no past history of bacterial endocarditis.

On physical examination, she had normal body habitus. Blood pressure was 130/70 mmHg; pulse was 80 bpm and regular. The jugular veins were not distended, the carotid pulsations were normal, and the lungs were clear. The apical impulse was diffuse; S1 was diminished. There was a grade 3/6 apical pan systolic murmur transmitted to the axilla. No opening snap, S3, or diastolic murmur was heard. There were no aortic murmurs. The ECG showed
normal sinus rhythm, complete right bundle branch block, and left-axis deviation. Chest roentgenogram showed enlargement of the left ventricle and left atrium. No valvular calcification was seen.

Cardiac catheterization, left ventriculography, and coronary angiography were performed with the following findings:

Left ventriculography showed excellent and uniform contraction of the left ventricle and a large regurgitant jet into the left atrium, which was filled completely within one beat. The mitral valve did not prolapse into the left atrium.

Coronary angiography revealed normal epicardial vasculature, no irregularities or narrowings, and normal runoff.

Interpretation

Mitral regurgitation was identified and quantified. There were no other valvular lesions. Although the LVEDP and left ventricular end-diastolic volume were above normal, the left ventricle contracted uniformly and vigorously, as judged by cineangiography. The ejection fraction of 0.79 and the end-systolic volume were normal. The slight elevation of pulmonary vascular resistance was mainly related to the low pulmonary blood flow (forward cardiac output) of 3.9 L/min (cardiac index = 2.0L/min/m²).

Systemic vascular resistance was substantially increased, perhaps representing excessive vasoconstriction in response to the decreased forward cardiac output. The increased systemic vascular resistance presented an augmented afterload to the left ventricle, worsening this patient's mitral regurgitation. Reduced systemic vascular resistance, induced by vasodilator therapy with a converting-enzyme inhibitor, an angiotensin receptor antagonist, an α-adrenergic blocker, or hydralazine would probably improve this patient's cardiac output and her symptoms of dyspnea on exertion.

AORTIC STENOSIS

Aortic stenosis may be valvular, subvalvular, or supravalvular. Valvular aortic stenosis is most often of the acquired calcific type, which develops on the substrate of a congenitally deformed (e.g., bicuspid) aortic valve. Valvular aortic stenosis also may be present from birth (congenital aortic stenosis), or it may develop as a consequence of rheumatic fever. Subaortic stenosis is of various types. Supravalvular stenosis is rare. All types of aortic stenosis can result in a significant systolic pressure difference between the left ventricle and the aorta. In subaortic stenosis, the gradient is between the main portion of the left ventricle and its outflow tract, although in “tunnel” subaortic stenosis there may be no discrete subvalvular chamber. In supravalvular stenosis, the gradient is just beyond the aortic valve, between the initial segment of the proximal aorta and the main segment of the ascending aorta. To facilitate surgical intervention, it is important to identify the site and nature of the obstruction in each instance. This is determined by both hemodynamics and angiography. In addition, left ventricular function and the presence or absence of aortic and mitral regurgitation should be evaluated. The left ventricle becomes progressively hypertrophied in aortic stenosis. The cardiac output is well maintained until the left ventricle dilates and fails; it then becomes progressively reduced. The following discussion focuses on valvular aortic stenosis in the adult.

The cardinal indications for cardiac catheterization in anticipation of surgery for all three types of aortic stenosis are left ventricular failure, angina pectoris, or syncope. Coronary angiography should be performed in essentially all adults being studied for evaluation of hemodynamically significant aortic stenosis.

Hemodynamic Assessment

In the hemodynamic assessment of valvular aortic stenosis, primary importance should be placed on obtaining simultaneous measurement of pressure and flow across the aortic valve. As discussed in Chapter 10, this permits calculation of the aortic orifice or valve area. In the typical adult with symptomatic aortic stenosis, the aortic valve area is reduced to 0.7 cm² or less. Occasionally, a valve of 0.8 to 0.9 cm² results in asymptomatic presentation, especially when there is concomitant coronary artery disease or hypertension or when the absolute value of cardiac output is high (e.g., a large patient, anemia, fever, thyrotoxicosis). When the aortic valve area is 0.5 cm² or less, severe aortic stenosis is present and cardiac reserve is minimal or absent.
For the typical adult patient with acquired aortic stenosis, the correlation between clinical severity and aortic valve area calculated by the Gorlin equation (see Chapter 10) is summarized in Table 29.1. If other cardiac disease is present (e.g., coronary disease, other valve disease, cardiomyopathy), the correlations listed in Table 29.1 are not applicable.

Most patients with aortic stenosis, particularly those with the clinical presentation of angina and/or syncope, have a normal cardiac output/index, normal right heart and PCW mean pressures, and normal LVEF. The LVEDP is usually increased, reflecting a stiff left ventricle, and there is a prominent A wave in PCW, left atrial, and left ventricular pressure tracings (Fig. 29.6). In more advanced cases, LVEF and cardiac output are depressed, and right heart and PCW mean pressures are elevated. Severe pulmonary hypertension with right-sided heart failure, ascites, and edema may come to dominate the picture. In these patients, the low-output state may lead to a reduction in the intensity of the characteristic systolic murmur, obscuring the diagnosis.

**FIG. 29.6.**

Pressure recordings in a patient with aortic stenosis. **A:** Left ventricular (LV) and central aortic (Ao) pressures recorded simultaneously. **B:** LV and femoral arterial (FA) pressures. The FA pressure is out of phase and exhibits distortion (higher systolic peak and lower end-diastolic pressure) characteristic of peripheral arterial pressures. (Reproduced with permission from Blitz LR, Kolansky DM, Hirshfeld JW Jr. Valve function: stenosis and insufficiency. In: Pepine CJ, Hill JA, Lambert CR, eds. 3rd ed. Baltimore: Williams & Wilkins, 1998.)

**Carabello's Sign**

An interesting hemodynamic finding, described by Carabello and coworkers (13), is a rise in arterial blood pressure during left heart catheter pullback in patients with severe aortic stenosis (Fig. 29.7). Pressure tracings from 42 patients with aortic stenosis who underwent continuous arterial pressure recording during left heart catheter pullback (withdrawal from the left ventricle to the central aorta of a catheter that had been placed in the left ventricle by retrograde technique) were examined. Increases in peripheral arterial pressure of 5 mm Hg or more were noted during withdrawal in 15 of the 42 patients. Fifteen (75%) of 20 patients with aortic valve area of 0.6 cm² or less demonstrated this phenomenon, but none of 22 patients with aortic valve area of 0.7 cm² or more showed such an increase. It was concluded that a rise in peak arterial pressure during left ventricular catheter withdrawal is an ancillary hemodynamic finding of critical aortic stenosis (Fig. 29.7). The mechanism of this phenomenon is most likely related to partial obstruction of an already narrowed aortic orifice by the retrograde catheter and relief of this obstruction when the catheter is withdrawn.

**FIG. 29.7.**

Left ventricular (LV) and femoral artery (FA) pressure tracings in a patient with severe aortic stenosis (aortic valve area, 0.4 cm²). During pullback of the retrograde catheter from LV to ascending aorta, the peak systolic femoral artery pressure increased (ΔP) by approximately 20 mm Hg. This sign is seen only in patients with aortic valve areas less than 0.6 cm². The mechanism of this phenomenon is believed to be partial obstruction of an already narrowed aortic orifice by the retrograde catheter and relief of this obstruction with catheter withdrawal. (From Carabello BA, et al. Changes in arterial pressure during left heart pull-back in patients with aortic stenosis. *Am J Cardiol* 1979;44:424.)

**Angiographic Assessment**

In patients with aortic stenosis, left ventriculography can yield important information, and I believe that it generally should be part of the catheterization procedure. It must be emphasized, however, that patients with left ventricular failure and high PCW pressure due to aortic stenosis may not tolerate the radiographic contrast load of left ventriculography. Adequate preventriculography preparation (e.g., intravenous furosemide, morphine, or oxygen) and use of non ionic or low-osmolality contrast agents are mandatory in such patients, and ventriculography should
not be done without careful consideration of risk versus benefit. The value to be obtained from left ventriculography includes assessment of the mitral valve (whether there is significant mitral regurgitation), detection of regional wall motion abnormalities or left ventricular aneurysm indicative of major coronary disease, and overall assessment of left ventricular function. In addition, wall thickness and left ventricular mass may be measured from the ventriculogram. Often this information can be obtained from echocardiography, and contrast left ventriculography can be avoided.

Aortography is generally not required in the patient with aortic stenosis unless the gradient is small and the aortic pulse pressure is wide. Selective coronary arteriography should be done in most patients with acquired calcific aortic stenosis, especially if chest pain is present.

**Catheterization Protocol**

1. Right-sided heart catheterization for measurement of right heart pressures and cardiac output.
2. Left-sided heart catheterization for measurement of the pressure gradient across the aortic valve and the LVEDP and for assessment of the presence or absence of a transmitral gradient (concomitant mitral stenosis). Retrograde crossing of a tight aortic valve may be difficult. From the brachial approach, many operators have been successful in crossing a tight aortic valve using a Sones catheter (Cordis Corporation, Miami Lakes, FL). The Cordis polyurethane Sones catheter has high torque control and tapers to a 5.5F tip, which often can be negotiated across a stenotic aortic valve without the aid of a guidewire. When a guidewire is required, a 0.35-inch-diameter straight wire passes easily through the Sones catheter and can help in crossing the aortic valve.

With a femoral approach, a pigtail catheter together with a straight guidewire protruded a short distance beyond the catheter tip is a widely used first approach to retrograde catheterization of the left ventricle in the patient with aortic stenosis; this method is illustrated in Chapter 4. On occasion, a right or left Judkins coronary catheter used together with a straight guidewire is successful in crossing a tight aortic valve in a patient with aortic stenosis. In one patient with calcific aortic stenosis and a very eccentric aortic valve orifice for whom all these approaches had failed, a left L2 Amplatz catheter with a straight guidewire was introduced successfully in retrograde catheterization of the left ventricle. An improved catheter design for crossing stenosed aortic valves has been developed by Feldman and coworkers (14) at the University of Chicago. Using this catheter (Feldman A catheter, Cook, Inc., Bloomington, IN), the authors found that the median time to cross the aortic valve retrograde was 30 to 40 sec in a group of 17 patients with a mean aortic valve area of 0.75 cm$^2$. If these approaches are not successful (or are not desirable in a particular patient), a transseptal approach may be used. In some laboratories, the transseptal approach is the primary technique for patients with aortic stenosis. In patients with aortic stenosis, it is highly desirable to measure transvalvular gradients as near as possible to the site of obstruction. Therefore, as seen in Fig. 29.6, the transaortic gradient measured with a catheter in the left ventricle and another catheter in the central aorta may differ from that obtained when arterial pressure is measured in the femoral artery. This problem is discussed in greater detail in Chapter 10. Newer double-lumen pigtail catheters (e.g., Cook Instruments) make it possible to measure left ventricular and central aortic pressures with a single catheter, avoiding the need for a separate arterial entry site. Another potentially important source of error in pressure measurement in patients with aortic stenosis can result from incomplete entry of a multiple side-hole catheter into the left ventricular chamber. Figure 29.8 illustrates this problem, with a pigtail catheter partially (A) or completely (B) within the left ventricular chamber. The partial entry pressures lead to a gross underestimation of the severity of the aortic stenosis.

3. Angiography according to the guidelines just discussed.

**FIG. 29.8.**

Left ventriculography demonstrates the stenotic orifice of the valve during systole as outlined by a jet of contrast material ejected into the aorta. The valve cusps may appear irregular, their mobility may be reduced, and often the number of cusps can be identified. In congenital aortic stenosis, the valve may form a funnel during systole. The ascending aorta is dilated (post stenotic dilatation), but the subvalvular area is widely patent. A subaortic membrane, with a small central orifice, or a subvalvular muscular ring may be seen. The characteristic changes of idiopathic hypertrophic subaortic stenosis may be observed. In supravalvular stenosis, the narrowing of the proximal aorta can be seen.

Aortography also can be helpful in evaluation of the patient with aortic stenosis. In “pure” aortic stenosis (no concomitant aortic regurgitation), aortography often demonstrates a negative jet of radiolucent blood exiting focally from the left ventricle. In congenital aortic stenosis, there may be upward doming of the aortic valve leaflets which, together with the central negative jet, gives the so-called Prussian helmet sign. In the patient with aortic stenosis who also has some aortic regurgitation, aortography permits a rough quantitation of the severity of the regurgitation. If interventional catheter techniques (e.g., balloon aortic valvuloplasty) are under consideration, determination of the extent of associated aortic regurgitation may become important in clinical decision making.

Hemodynamic assessment often can detect the presence of mixed significant aortic stenosis and regurgitation, as illustrated by the patient whose pressure tracings are shown in Fig. 29.9. This 78-year-old man had the unusual combination of hemodynamically significant aortic stenosis (70 mm Hg gradient) and significant aortic regurgitation (grade 3+, regurgitant fraction 48%).

**Case 5: Aortic Stenosis Without Appreciable Cardiomegaly**

L.C. was a 48-year-old married woman with a history of rheumatic fever in childhood. Six months before admission, she noted increasing exertional dyspnea and decreased effort tolerance. She had had dizziness but no syncope or angina.

Physical examination was normal except for the heart. There was a forceful apex impulse in the midclavicular line in the fifth interspace. Rhythm was regular. S1 and S2 were normal. The only murmur was a grade 2/6 ejection-type systolic murmur, maximal along the left sternal border and transmitted to the apex and into the carotids. No thrill was detected. The carotid pulsations exhibited a slow upstroke but were of normal amplitude. The ECG revealed left ventricular hypertrophy and strain. Chest radiographs showed a heart of normal overall size. There was a little rounding in the region of the left ventricle. The other cardiac chambers appeared normal, as did the lungs. At fluoroscopy, calcification was observed in the region of the aortic valve.

The findings at cardiac catheterization were as follows:

Left ventriculography showed a vigorously contracting, normal-sized left ventricle and a calcified aortic valve with three cusps. The valve leaflets were almost immobile. A jet was seen passing through the valve that almost immediately became obscured by the radiopacity of the aorta. There was a rather discrete post stenotic dilation of the ascending aorta just above the aortic valve.

**FIG. 29.9.**

Left ventricular (LV) and femoral artery (FA) pressure tracings in a 78-year-old man with increasing dyspnea on exertion and one episode of pulmonary edema. In this case, femoral artery and central aortic pressures were almost superimposable. There is a 70-mm Hg peak-to-peak systolic gradient, but there is also unusually rapid aortic diastolic runoff with equilibration (diastasis) of end-diastolic LV and FA pressures. This latter finding suggested significant aortic regurgitation, which was confirmed by aortography.

**Interpretation**

The moderately severe calcific aortic stenosis in this woman was probably rheumatic in origin. The left ventricle contracted well, as indicated by an LVEF of 0.69 and a normal cardiac output. The elevated LVEDP at rest was compatible with a decreased chamber distensibility from hypertrophy.
Case 6: Aortic Stenosis with Appreciable Cardiomegaly

A.H., a 77-year-old man, was well until 3 years before admission, when exertional dyspnea, orthopnea, fatigue, and peripheral edema appeared. Despite therapy, these symptoms increased progressively to the point of invalidism. He had mild angina and had had two syncopal episodes.

On physical examination, the blood pressure was 110/80 mm Hg; the pulse was 78 beats per minute and regular; respirations were 24 per minute. The carotids were of small volume with slow upstroke. Neck veins were moderately distended. There were basilar rales audible over both lungs. The point of maximal impulse was in the sixth inter space 2 cm within the anterior axillary line, diffuse and forceful. There was no parasternal heave. A grade 2/6 aortic systolic ejection murmur was heard all along the left sternal border and over both carotid arteries. The liver was two palpable finger breadths below the right costal margin. There was slight pitting edema of both lower legs. The ECG showed left ventricular hypertrophy and strain pattern. Chestroentgenogram showed enlargement of the left ventricle, calcification in the region of the aortic valve, moderate redistribution of vascular markings to the upper lobes of the lungs, and a small amount of pleural fluid on the right.

Cardiac catheterization yielded the following results:

Left ventriculography was performed only after pretreatment with intravenous furosemide and showed a large dilated left ventricle with uniformly poor contractions in systole. There was no mitral or aortic regurgitation. The aortic valve had two leaflets that appeared ragged and were heavily calcified. There was considerable dilation of the ascending aorta. Left ventriculography was tolerated well, and coronary angiography (two injections of the left coronary artery and one injection of the right coronary artery) revealed the absence of significant coronary artery obstruction.

**Interpretation**

There was severe calcific aortic stenosis, as indicated by a calculated valve area of 0.4 cm². Severe left ventricular failure was present, as indicated by left ventricular dilatation, high LVEDP (35 mm Hg), uniformly poor contraction by cineangiography, an LVEF of only 0.30, and a very low cardiac output. The aortic obstruction was severe. The left ventricle was so decompensated that it generated a peak systolic pressure of only 184 mm Hg (instead of 250 to 300 mm Hg, as would be expected with a normal cardiac output), and the mean transaortic pressure gradient was only 40 mm Hg.

The PCW pressure of 29 mm Hg explained the rales heard at both lung bases as well as the patient's shortness of breath. The pulmonary hypertension was caused in part by the elevated left ventricular diastolic pressure (passive rise) and in part by reactive pulmonary hypertension, as revealed by the finding of a pulmonary vascular resistance of 683 dyn·sec·cm⁻⁵, more than five times normal.

The pressure load on the right ventricle resulted in its decompensation, as indicated by a mild elevation of the right ventricular diastolic and right atrial pressures. The clinical counterpart was slight distention of the neck veins, an enlarged liver, and peripheral edema.

**AORTIC REGURGITATION**

The dynamic effects of aortic regurgitation are caused by regurgitation of blood from the aorta to the left ventricle in diastole. The magnitude of the regurgitation depends on the size of the regurgitant orifice, the pressure difference between the aorta and the left ventricle in diastole, and the duration of diastole. The regurgitant aperture may be as large as 1.0 cm², but regurgitation is generally severe when the aperture is more than 0.5 cm². The total left ventricular stroke volume increases and equals that which supplies the body (forward flow) plus that which is regurgitated. The amount of blood regurgitated may be as much as 60% or more of the systolic discharge. The regurgitation usually occurs in early diastole.

**Hemodynamic Assessment**
The large stroke volume entering the aorta with systole produces an elevated systolic pressure, whereas the regurgitation produces a lowered aortic diastolic pressure (Fig. 29.10). Left ventricular workload increases progressively with the magnitude of regurgitation. This is a result not only of the raised stroke volume and the rise of systolic pressure but also of the high left ventricular wall stress that develops when a dilated left ventricle contracts to produce a given pressure (LaPlace’s law). Dilatation and hypertrophy of the left ventricle are invariable consequences of aortic regurgitation. The heart may become the largest encountered in cardiac pathology—the so-called cor bovinum. Up to a point, the forward cardiac output is well maintained. The addition of blood regurgitated to the normal inflow from the left atrium increases the diastolic volume of the left ventricle, leading to a more forceful contraction (Starling’s law). With time, the fraction of end-diastolic volume ejected per beat (LVEF) becomes diminished, reflecting impaired myocardial function. Furthermore, the left ventricle may operate with an excessive end-systolic volume—another index of left ventricular dysfunction.

**FIG. 29.10.**

Left ventricular (LV) and aortic (Ao) pressure tracings in a patient with severe aortic insufficiency, secondary to rheumatic heart disease. In this condition, the aortic and left ventricular pressures may equalize in late diastole, a phenomenon occasionally termed diastasis.

**FIG. 29.11.**

Left ventricular (LV) and pulmonary capillary wedge (PCW) pressures in a patient with acute aortic regurgitation due to infective endocarditis. Note the unusual waveform of the LV pressure with its striking late diastolic rise, loss of clear a wave, and high elevation of LVEDP (approximately 45 to 50 mm Hg). LV diastolic pressure rises in late diastole to exceed left atrial and pulmonary wedge pressures (downward arrows), forcing premature closure of the mitral valve. (From Mann T, et al. Assessing the hemodynamic severity of acute aortic regurgitation due to infective endocarditis. *N Engl J Med* 1975;293:108.)

**Premature Mitral Valve Closure**

The reflux of blood from the aorta into the left ventricle in diastole, added to the blood streaming through the mitral valve from the left atrium, results in a rapid rise in left ventricular pressure early in diastole. The mitral valve may close prematurely because the regurgitating blood may raise the left ventricular diastolic pressure to exceed that in the left atrium. This is particularly common in acute aortic regurgitation, where the sudden onset of severe regurgitation into a normal-sized left ventricle leads to striking elevations in left ventricular diastolic pressure. In the case illustrated in Fig. 29.11, LVEDP approaches 50 mm Hg, and left ventricular diastolic pressure exceeds left atrial (or PCW) pressure for almost half of diastole. This reversal of pressures is associated with premature mitral valve closure, which may be seen on the echocardiogram.

Another example of premature closure of the mitral valve in association with severe aortic regurgitation is shown in Fig. 29.12. These tracings were recorded during cardiac catheterization in a 71-year-old man who had previously undergone aortic valve replacement for aortic stenosis. After doing extremely well for more than 5 years, he suddenly developed marked shortness of breath and a new murmur of aortic regurgitation. Pressure recordings show that the left ventricular diastolic pressure exceeds left atrial (PCW) pressure by the end of the first third of the diastolic filling period. Also, complete diastasis of aortic and left ventricular pressures occurs by mid-diastole, at which point aortic regurgitation ceases because there is no longer any gradient driving the regurgitant flow. As expected, this patient’s diastolic murmur was blowing in quality, decrescendo, and ended by mid-diastole.

**FIG. 29.12.**

Severe aortic regurgitation in a 71-year-old man with a prosthetic aortic valve. There is diastasis between left ventricle (LV) and aorta. Also, LV diastolic pressure exceeds pulmonary capillary wedge (PCW) pressure early in diastole. ECG, electrocardiogram; FA, femoral artery. (See text for details.)
Acute Versus Chronic Aortic Regurgitation

The typical hemodynamic findings in acute versus chronic aortic regurgitation have been reported by Mann et al. (15) and are presented in Table 29.2. As can be seen, widened pulse pressure is characteristic only of chronic aortic regurgitation, reflecting both the enormous stroke volume associated with this condition and the tachycardia commonly seen in patients with acute aortic regurgitation. This may give rise to a situation in which a high LVEDP exists in the noncompliant left ventricle in the presence of little if any elevation of the mean pressure in the left atrium. With time and with the severity of the leak, the mean diastolic pressure of the left ventricle rises, and when this happens, left atrial and PCW pressures rise.

Another hemodynamic finding in aortic regurgitation is the amplification of peak systolic pressure in peripheral arteries (especially the femoral and popliteal arteries), so that peak systolic femoral artery pressure may exceed central aortic pressure by 20 to 50 mm Hg. This is essentially an exaggeration of a normal phenomenon (see Chapter 7), but it emphasizes the importance of central aortic pressure measurement in aortic regurgitation.

Angiographic Assessment

Aortic cineangiography (aortography) yields a graphic demonstration of the severity and dynamics of the regurgitation. Qualitative assessment is subjective, as for mitral regurgitation. A scale of 1+ to 4+ may be used, employing the following definitions to aid discrimination of these four degrees of regurgitation. In 1+ regurgitation (mild), a small amount of contrast material enters the left ventricle in diastole; it is essentially cleared with each beat and never fills the ventricular chamber. More contrast material enters with each diastole in 2+ (moderate) regurgitation, and faint opacification of the entire chamber occurs. With moderately severe (3+) regurgitation, the left ventricular chamber is well opacified and equal in density with the ascending aorta. Severe (4+) aortic regurgitation is characterized by complete, dense opacification of the left ventricular chamber in one beat, and there is the appearance that the left ventricle is more densely opacified than the ascending aorta.

Quantitative assessment of aortic regurgitation involves calculation of the regurgitant fraction (RF), as described in Chapter 16. The same scale of interpretation holds as for mitral regurgitation, with RF less than 20% corresponding to mild regurgitation; 20% to 40%, moderate; 40% to 60%, moderately severe; and more than 60%, severe aortic regurgitation.

Part of the angiographic assessment of aortic regurgitation involves assessment of the aortic valve leaflets (mobility, calcification, number of leaflets), the ascending aorta (extent and type of dilatation), and possible associated abnormalities (e.g., coronary lesions, sinus of Valsalva aneurysm, dissecting aneurysm of the aorta, ventricular septal defect). All these aspects are best evaluated in the left anterior oblique view.

Catheterization Protocol

1. Right-sided heart catheterization for measurement of right heart pressures and cardiac output.
2. Left-sided heart catheterization for measurement of central aortic pulse pressure and detection of transvalvular gradients (if any), of diastasis between left ventricle and aorta (if present, Fig. 29.12), and of relative height of LVEDP compared with PCW or left atrial mean pressure.
3. Angiography, including left ventriculography, aortography, and possibly coronary angiography (if indicated clinically).
4. If resting hemodynamics are normal, consider stress intervention, such as dynamic exercise.

TRICUSPID REGURGITATION

Tricuspid regurgitation can be functional or organic. Functional tricuspid regurgitation is thought to be caused by right ventricular dilatation and failure as a result of excessive right ventricular afterload. Most commonly, this is caused by pulmonary hypertension from mitral stenosis, cardiomyopathy, primary pulmonary hypertension, cor pulmonale, or pulmonary embolism.
“Organic” tricuspid regurgitation implies disease of the tricuspid valve or its supporting apparatus and is seen most commonly with bacterial endocarditis, rheumatic heart disease, or right ventricular infarction.

**Hemodynamic Assessment**

In tricuspid regurgitation, either organic or functional, the primary hemodynamic finding is a large systolic wave in the right atrial pressure tracing. Tracings of jugular venous pulsations show a, c, and v waves in the normal subject; in the patient with moderate tricuspid regurgitation, there is a fourth pulsation, the s wave. This systolic wave precedes and blends with the normal venous filling (v) wave, and in severe tricuspid regurgitation the s and v waves form a single regurgitant systolic wave. As can be seen in Fig. 29.13, the right atrial pressure tracing in severe tricuspid regurgitation resembles the right ventricular pressure tracing. In the most extreme cases, the right atrial and ventricular pressure tracings are virtually superimposable, which is to be expected because the right atrium and ventricle are physiologically a common chamber in such cases.

**FIG. 29.13.**

Right atrial (RA) and ventricular (RV) pressure tracings in a 75-year-old woman with rheumatic heart disease. There is severe organic tricuspid regurgitation, with the RA waveform resembling the RV pressure.

The hemodynamic distinction between organic and functional tricuspid regurgitation is difficult. Generally, if the patient with severe tricuspid regurgitation has a right ventricular systolic pressure greater than 60 mm Hg, the tricuspid regurgitation is functional, whereas if the right ventricular systolic pressure is 40 mmHg or less, there is a substantial organic component. This distinction is of practical importance in terms of surgical correction, because functional tricuspid regurgitation improves substantially solely with correction of the right ventricular hypertension (e.g., after balloon valvuloplasty or corrective surgery for mitral stenosis), whereas the patient with major organic tricuspid regurgitation may not survive cardiac surgery unless the operation includes tricuspid valve replacement or tricuspid annuloplasty.

**Angiographic Assessment**

The angiographic demonstration of tricuspid regurgitation is usually accomplished by right ventricular cineangiography in the right anterior oblique projection, as discussed in Chapter 12. Some artificial tricuspid regurgitation is seen because of the presence of the catheter across the tricuspid valve, but this is usually minor. It is important to choose a catheter type, position, and injection rate that avoid extra systoles, because a run of ventricular tachycardia makes it impossible to evaluate the degree of tricuspid regurgitation; these considerations are discussed in Chapter 12. There has been much experience with the Grollman, pigtail, and Eppendorf catheters situated in the middle right ventricle or right ventricle outflow tract, with injection rates of 12 to 18 mL/sec depending on right ventricle size and irritability. A scale of 1+ to 4+ is used to grade the severity of tricuspid regurgitation, with the criteria of definition being similar to those described for mitral regurgitation. In some circumstances, a right atrial cineangiogram in take right anterior oblique projection can be used for assessment of tricuspid regurgitation; in this instance, a negative jet (unopacified blood) from right ventricle to right atrium shows the regurgitation.

The cardiac catheterization protocol depends on the associated conditions.

**TRICUSPID STENOSIS**

Previously, this rare condition was seen only in patients with rheumatic heart disease and mitral stenosis. Today, stenosis of a prosthetic tricuspid valve (placed originally as treatment for tricuspid regurgitation) accounts for the majority of the cases seen in most major medical centers. The clinical diagnosis may be difficult, especially if the patient is in atrial fibrillation. Diagnosis is aided by the characteristic finding of an increased jugular venous pressure with blunting or absence of the y descent. One patient seen by me had severe stenosis of her native mitral, aortic, and tricuspid valves. This was a 43-year-old woman with a history of repeated bouts of rheumatic fever in childhood, whose major complaint was fatigue and "blackouts.”
Hemodynamic Assessment

The *sine qua non* of tricuspid stenosis is an apandiaistic gradient across the tricuspid valve. The gradient is usually small (4 to 8 mm Hg) and may be missed unless a careful assessment is made. Two catheters (or a single catheter with a double lumen) and simultaneous measurement of right atrial and right ventricular pressures should be used if there is any doubt about the presence of this condition. However, a careful right ventricle-to-right atrial pullback using a standard catheter serves to confirm or eliminate this diagnosis with reliability in most cases. The tricuspid valve area is calculated by the formula given in Chapter 10. Tricuspid stenosis is usually of clinical and hemodynamic significance when the tricuspid valve area is less than 1.3 cm².

Angiographic Assessment

The valve is usually calcified and shows decreased mobility. There may be associated right atrial dilatation and some tricuspid regurgitation.

The cardiac catheterization protocol depends on the associated lesions.

**PULMONIC STENOSIS AND REGURGITATION**

Pulmonic stenosis is essentially a congenital condition. Pulmonic regurgitation is usually functional and a consequence of severe pulmonary hypertension. When the pulmonary artery pressure exceeds 100 mm Hg systolic, there is usually some pulmonic regurgitation. This may lead to widening of the pulmonary artery pulse pressure and an increase in right ventricular end-diastolic pressure. Angiographic assessment of pulmonic regurgitation is difficult because the angiographic catheter lying across the pulmonic valve may cause artifactual regurgitation. Echocardiography is far superior to angiography in assessing pulmonic regurgitation.

The cardiac catheterization protocol depends on associated conditions.

**RELATIVE STENOSIS OF PROSTHETIC VALVES**

An unusual case of relative tricuspid stenosis, mitral stenosis, and aortic stenosis in a 60-year-old man is shown in Fig. 29.14 and illustrates an important point concerning function of prosthetic cardiac valves. This man had mitral valve replacement with a Harken disc valve in 1969 for rheumatic mitral regurgitation. He did well until 1980%, when he presented with left- and right-sided heart failure and was found at cardiac catheterization to have severe aortic and tricuspid regurgitation but normal function of the mitral prosthetic valve. Aortic valve replacement (Starr-Edwards prosthesis) and tricuspid valve replacement (porcine prosthesis) led to improvement, but over the following years he required large amounts of diuretic therapy to remain free of edema and pulmonary congestion. Echocardiographic assessment of his prosthetic valves demonstrated apparently normal function, and left ventricular contraction was vigorous.

**FIG. 29.14.**

Pressure tracings in a 60-year-old man with high cardiac output and significant pressure gradients across normally functioning tricuspid, mitral, and aortic valve prostheses—(A) from the right ventricle (RV) and right atrium (RA); (B) from the left ventricle (LV), femoral artery (FA), and pulmonary capillary wedge position (PCW). ECG, electrocardiogram.

Because of persistent left- and right-sided heart failure, cardiac catheterization was undertaken in 1985. The porcine tricuspid valve was crossed antegrade with a Swan-Ganz catheter, and the Starr-Edwards aortic prosthesis was crossed retrograde with a Sones catheter to obtain the pressure measurements shown in Fig. 29.14. As can be seen, significant pressure gradients were present across tricuspid, mitral, and aortic prostheses. A surprising finding was an elevated
cardiac output, measured by both Fick and thermodilution methods. The oxygen consumption index was 148 mL/min/m² and the arteriovenous oxygen difference was 29 mL O₂/L, giving a Fick cardiac index of 5 L/min/m² and a cardiac output of 10 L/min. Using the Gorlin formula (Chapter 10), aortic valve area was calculated to be 1.3 cm², mitral valve area 1.6 cm², and tricuspid valve area 2.4 cm²; these values were all consistent with the known effective orifice areas of the particular prosthetic valves implanted and did not signify prosthetic valve dysfunction or stenosis. Therefore, a high cardiac output state caused substantial pressure gradients to occur across the patient's three prosthetic valves, resulting in the clinical picture of biventricular failure. Thyroid function tests were normal, and a search for other causes of high output state (e.g., arteriovenous fistula, Paget's disease) was unrevealing. This patient responded to thiamine supplementation, β-blockade, and diuretic therapy with spironolactone and furosemide; evidence of high-output state receded and a vigorous diuresis ensued.

Catheter Passage across Prosthetic Valves

As illustrated in the case just described, it has become routine to cross prosthetic valves with catheters in an attempt to assess their function or the function of other valves. Published reports have documented the safety of this procedure in a large number of patients (16, 17) with a variety of prosthetic valves. Based on my own experience and anecdotal experience reported to me by many others, I offer the following guidelines. First, porcine valves may be crossed retrograde or antegrade safely with a variety of catheters. For retrograde crossing of a porcine prosthetic valve in the aortic position, a pigtail catheter is usually highly effective. The pigtail catheter tip is rested on top of the valve's leaflets as they protrude into the aorta, high above the sewing ring, and is gently advanced until it prolapses into the left ventricular chamber. Antegrade crossing of a porcine tricuspid prosthesis is accomplished easily with the use of a balloon-flotation catheter, as described in the preceding section. Retrograde crossing of a ball-valve (e.g., Starr-Edwards) prosthesis in the aortic position may be accomplished easily by a 7F or 8F Sones catheter with or without guidewire assistance. The pigtail catheter also may be advanced into the left ventricle over a guidewire across a ball-valve prosthesis, but the wire should be reinserted for catheter withdrawal to avoid hooking the pigtail on the metal cage. Although some operators have crossed low-profile disc-valve prostheses (e.g., Bjork-Shiley valve) retrograde without complications, instances of catheter entrapment with such crossings have been reported (18). Also, Dr. Viking Bjork has stated specifically that the Bjork-Shiley valve must not be crossed retrograde, based on his own large experience. When restudy has been required in his patients, a transseptal approach has been used. Accordingly, one should not attempt to cross a Bjork-Shiley valve or any low-profile disc valve prosthesis retrograde.

ACKNOWLEDGMENT

Some material in this chapter has been retained from the first and second editions, to which Dr. Lewis Dexter had contributed.