# Evaluation of Prosthetic Valve Dysfunction With the Use of Echocardiography

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Prosthetic heart valves (PHVs) are classified as either mechanical or biological. Each valve type has its own risk-to-benefit ratio, unique hemodynamic profile, and Doppler findings, which are also affected by the valve size and the patient's body surface area. Transthoracic echocardiography, along with two- and three-dimensional transesophageal echocardiography, including color and spectral Doppler, are each important for the comprehensive evaluation of PHVs and to identify the presence and mechanism of valve dysfunction.

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**KEY WORDS**

Prosthetic heart valve • Transthoracic echocardiography • Transesophageal echocardiography • Doppler

Heart valve replacement, initially introduced in the 1960s, has dramatically improved the outcome of patients with valvular heart disease; over 280,000 valves are implanted worldwide and approximately 90,000 are implanted in the United States.[1] Although the majority of prosthetic heart valves (PHVs) are implanted either in the aortic or mitral position, tricuspid and pulmonic prostheses are also available and in use. PHVs are classified as mechanical or biological, and each valve type has its own risk-to-benefit ratio (Table 1). Mechanical valves use a monoleaflet or bileaflet design, or a caged ball design. Bioprosthetic valves in both the mitral and aortic position have three cusps. They are usually stented; more recently, however, stentless bioprosthetic aortic valves have been developed. Mechanical valves can only be implanted surgically, although recent advances have led to percutaneous implantation of bioprosthetic valves.

This article contains supplementary material which may be found online at www.medreviews.com.

**TABLE 1**

**Advantages and Disadvantages of Mechanical and Bioprosthetic Valves**

| | Advantages | Disadvantages |
|---|---|---|
| Mechanical | Long-term durability | Need for chronic long-term anticoagulation |
| Bioprosthetic | No need for intensive anticoagulation | Faster structural deterioration, especially in younger patients |

## Echocardiographic Evaluation of PHVs

As with native valve disease, PHV dysfunction may manifest with acute clinical findings, have progressive chronic deterioration, or be asymptomatic. Data regarding the date of surgery, type of valve implanted and its size, along with the patient's heart rate, blood pressure, height, weight, and body size, facilitate valve assessment. Each type of valve has a unique hemodynamic profile and Doppler findings, which are also affected by the valve size and the patient's body surface area (BSA). Homografts, stentless bioprosthetic valves, and percutaneously implanted valves generally have flow dynamics that are close to those of native valves, whereas mechanical valves and stented bioprostheses have varying degrees of obstruction to flow.

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Echocardiography is the initial and most widely used imaging modality for evaluation of PHVs and screening for PHV dysfunction. Fluoroscopy, computed tomography, and magnetic resonance imaging can also provide additional data to improve assessment of PHV dysfunction.

Transthoracic echocardiography (TTE) is the standard method used to assess valve gradients and image the valve leaflets; however, TTE is limited in the setting of biological PHVs due to reverberations and acoustic shadowing caused by the prosthetic valve annulus. With mechanical valves, the annulus and leaflets cause acoustic shadowing and reverberations, obscuring the valve leaflets.[2,3] Due to the proximity of the esophagus to the left atrium and surrounding structures, transesophageal echocardiography (TEE) provides superior visualization of valvular anatomy, especially when evaluating mitral and tricuspid prostheses, paravalvular leaks, and prosthetic valve vegetations, abscesses, or thrombi.

After any valve replacement, patients should have serial echocardiographic studies to monitor valve function and to identify any degenerative changes in bioprosthetic valves.[4] It is an American College of Cardiology/American Heart Association guideline recommendation to perform follow-up TTE at 6 weeks to 3 months after valve replacement (Class I, level of evidence [LOE] B) and to perform echocardiographic follow-up if there is any clinical suspicion suggesting PHV dysfunction (Class I, LOE C). Regular echocardiographic follow-up is not recommended in asymptomatic patients. However, an annual TTE is recommended for patients starting 10 years after implantation, even if they are asymptomatic (Class IIa, LOE C).[4]

Table 2 summarizes the different echocardiographic parameters and variables that should be assessed when evaluating PHVs. Values are presented within the range of the varying normal values of the differing PHVs. For patients with either mechanical or stented bioprostheses, normal values differ according to the specific PHV, and are also affected by patient-specific factors (please see www.medreviews.com for supplemental Appendix A and B).[5-7] A postoperative two-dimensional (2D) Doppler echocardiography study performed when the patient is asymptomatic can facilitate future assessments when compared with serial follow-up studies.[4]

## Two- and Three-Dimensional Visualization of Leaflet Morphology and Mobility

Initial evaluation of a PHV should include 2D and three-dimensional (3D) visualization of the valvular ring, assessment of leaflet mobility, and evaluation for the presence of any calcifications, thickening, vegetation, abscesses, or the formation of either a thrombus or pannus (Figures 1-3).[8] Mild valve thickening can be the first sign of bioprosthesis failure, as can the presence of calcifications or a tear. All of these findings should initiate a closer follow-up. When evaluating mechanical prostheses, the presence of impaired disc excursion or an immobile leaflet suggests PHV dysfunction. However, the evaluation of leaflet motion in mechanical PHVs, even when using TEE, can be challenging due to artifacts and reverberations. Fluoroscopy is

## TABLE 2

### Abnormalities Encountered on the Echocardiographic Evaluation of Prosthetic Heart Valves

| Parameters | Comments |
|---|---|
| | **Visualization by Two- and Three-dimensional Imaging** |
| Leaflet morphology | |
| - Calcifications | Seen as bright echoes of the cusps/leaflets |
| - Thickening | Mild thickening can suggest valve failure |
| - Tear | A flail cusp/leaflet |
| Impaired leaflet/disc motion | Inadequate leaflet or disc motion or an immobile leaflet can indicate the presence of pannus or thrombus |
| Inspection of the valvular ring for separation from the native annulus and the presence of a rocking motion of the prosthesis | In the aortic position, rocking motion is invariably a sign of dehiscence; can be evident in a normal mitral prosthesis when there is retention of the native leaflets allowing for increased mobility[7] |
| Microbubbles/cavitation bubbles | Seen only in the presence of mechanical PHV; small, round, and echogenic echoes that occur at the inflow zone of the valve; can vary by the type of the mechanical prosthesis[9] |
| Sutures | Thick (usually $>$ 1 mm), linear, even-spaced echoes seen around the sewing ring of the PHV; usually immobile but if elongated they can be mobile |
| Strands | Thin (usually $<$ 1 mm), filamentous structures with variable length that are usually seen in the inflow side (atrial side for MV, ventricular side for AV); more common in mechanical than in biological PHV[10,11]; have been associated with cerebral events but their clinical significance is unknown |
| Masses on the valve | These can include findings consistent with but not limited to vegetation or a thrombus (as opposed to pannus, which is less evident on echocardiography); clinical presentation can usually aid in the differentiation of these findings |
| Abscess | Usually appears as an echolucent structure, irregularly shaped, most commonly seen adjacent to the prosthetic ring or as thickening of the aortic wall adjacent to the aortic prosthetic valve |
| | **Doppler** |
| Measure the gradient across the valve: $P = 4V^2$ | High transprosthetic gradient can be caused due to:<br>- Patient–prosthesis mismatch[a]<br>- Valvular obstruction due to thrombus, pannus, or vegetation<br>- Subvalvular obstruction<br>- High stroke volume (in the presence of bradycardia or significant regurgitation)[b]<br>- Pressure recovery phenomenon |
| $EOA = SV/VTI_{PrV} = Diameter_{LVOT} X\ VTI_{LVOT}/VTI_{PrV}$ | The manufacturer's labeled prosthesis dimensions cannot be substituted for the LVOT diameter |
| $DVI = VTI_{MV}/VTI_{LVOT}$ (for MV)<br>$DVI = VTI_{LVOT}/VTI_{AV}$ (for AV) | DVI is not affected by high output states; DVI is not affected by regurgitation when evaluating aortic PHVs; however, for mitral prostheses evaluation, the DVI is affected by regurgitation; can be elevated in hyperdynamic states, small valve size, and tachycardia |
| Mitral inflow, peak[c] E velocity – can be elevated either in stenosis or regurgitative states | E $<$ 1.9 m/s is usually normal for prosthetic valves; for some valves an E of up to 2.4 m/s can be normal for mechanical valves[6,7,15,48] |
| [c]Pressure half time | Should not be obtained in patients with AV block, tachycardia, or any other condition when there is a short diastolic filling period or the E and A waves are merged[7] |
| | **Color Doppler** |
| Assess for regurgitation jet/s | |
| - Physiologic | Minor regurgitation is normal in all prosthetic mechanical valves with patterns varying according to valve type; usually this is a short and narrow jet, with low velocity |
| - Pathologic | |
| Valvular (central) | Large and wide jets; mostly seen in bioprosthesis |
| Paravalvular | Can be seen in both mechanical and bioprostheses; usually asymmetric and eccentric |
| | **Other Variables That Should Be Evaluated** |
| - Pulmonary artery pressures<br>- Right ventricular size and function<br>- Left ventricular size and function<br>- Pericardial disease | Parameters should be compared to those obtained at baseline shortly after PHV implantation, preferably when the patient is asymptomatic |

[a]The most frequent cause of high postoperative gradients.[1]
[b]In patients with high gradients due to significant regurgitation, the DVI will be high ($>$ 0.35 for aortic and $>$ 0.45 for mitral), opposed to obstruction in which the increased gradients are accompanied by a low DVI.[1]
[c]Specific for evaluation of mitral valve prosthesis.
AV, aortic valve; DVI, dimensionless valve index; E, early; EOA, effective orifice area; LVOT, left ventricular outflow tract; MV, mitral valve; PrV, prosthetic valve; PHV, prosthetic heart valve; VTI, velocity time integral.

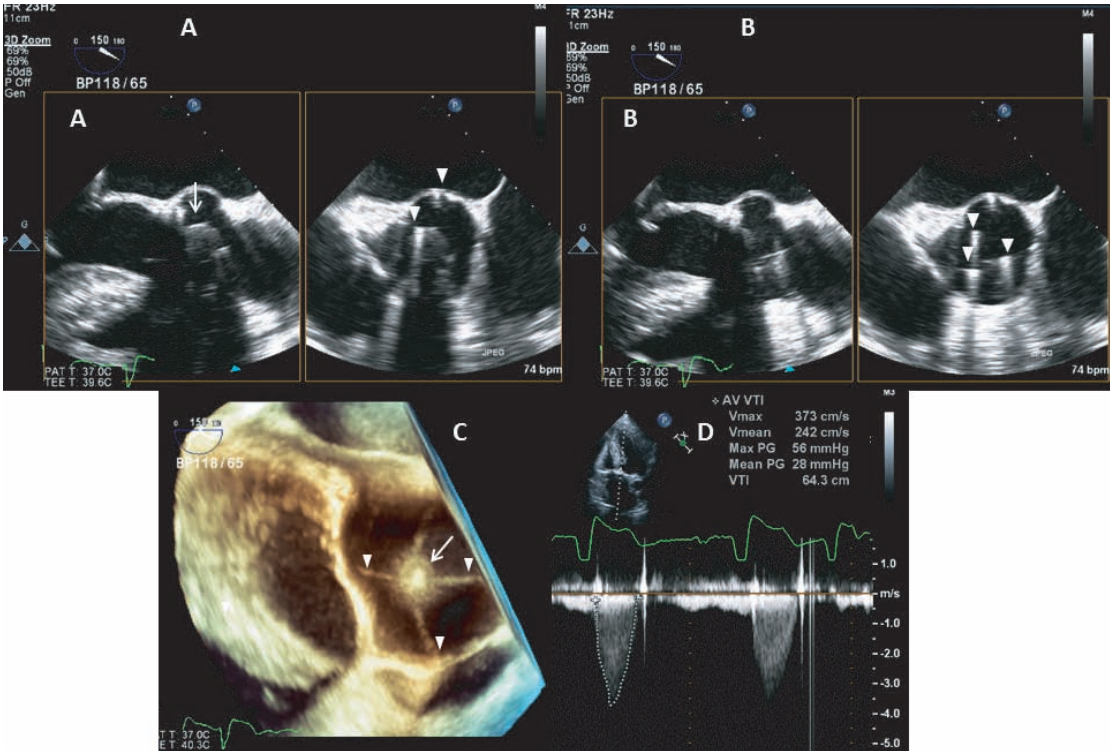
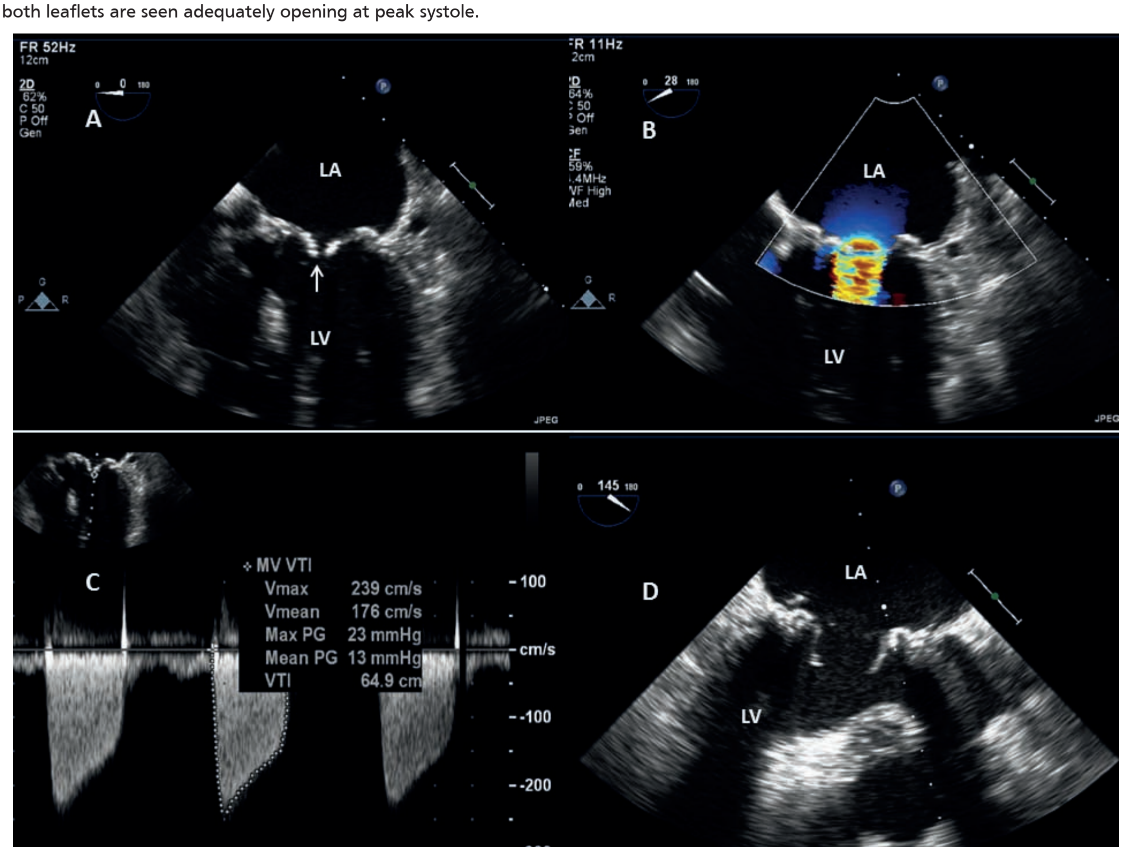



**Figure 1.** An aortic Starr-Edwards (Edwards Lifesciences, Irvine, CA) mechanical prosthesis. **(A)** Transesophageal biplane images through the aortic valve showing a mechanical Starr-Edwards (ball in cage) valve during systole **(A)** and diastole **(B)**. **(C)** Three-dimensional transesophageal echocardiographic image of the valve showing the ball (*arrow*) and cage struts (*arrowheads*). **(D)** On transthoracic Doppler echocardiography the mean pressure gradient is 28 mm Hg with a peak pressure gradient of 56 mm Hg in the presence of a normal functioning valve.

**Figure 2.** Stenosis of a bioprosthetic mitral valve. **(A)** Transesophageal echocardiographic imaging of a bioprosthetic mitral valve demonstrating restricted opening at peak systole (*arrow*). **(B)** Color-flow Doppler shows turbulent diastolic flow across the valve. **(C)** Spectral Doppler confirms a peak E wave of 2.4 m/s with a peak pressure gradient of 23 mm Hg and a mean pressure gradient of 13 mm Hg consistent with significant bioprosthetic mitral valve stenosis. **(D)** Postoperative replacement of the valve; both leaflets are seen adequately opening at peak systole.



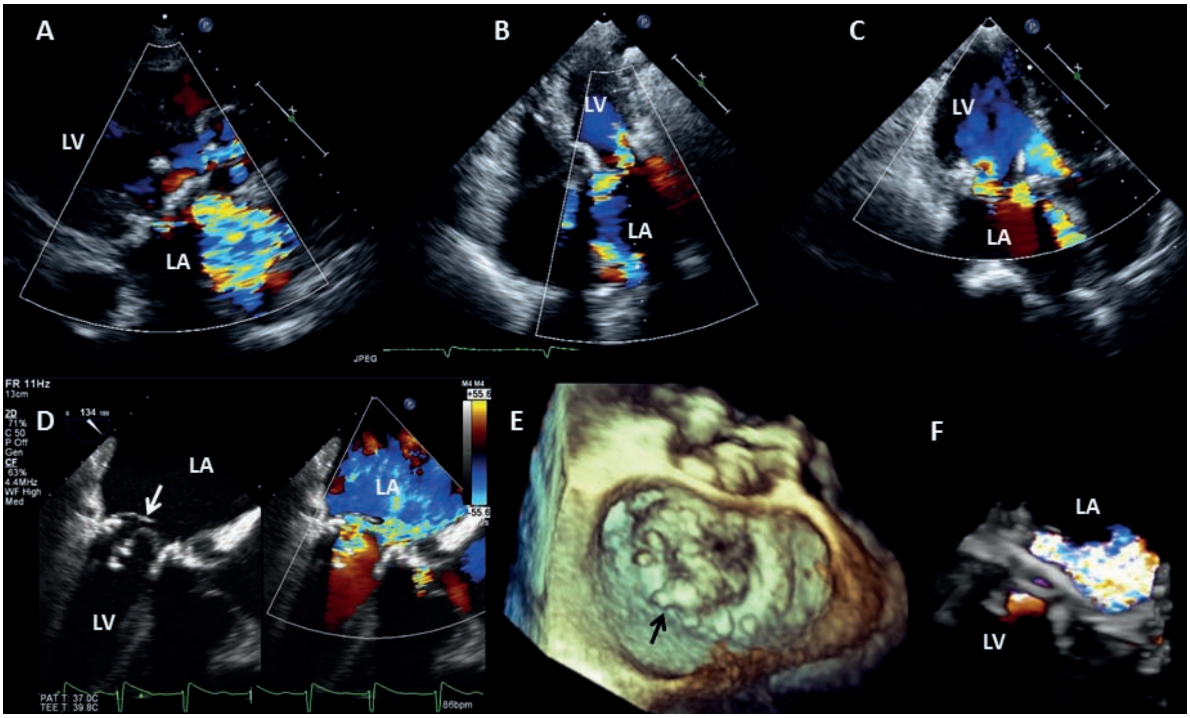



**Figure 3.** Bioprosthetic mitral valve with severe regurgitation due to valve degeneration. Top row: Transthoracic color Doppler images in the **(A)** parasternal long axis, **(B)** four-chamber, and **(C)** three-chamber view showing severe bioprosthetic mitral valve regurgitation with a varying amount of shadowing from the valve struts. Bottom row: Transesophageal echocardiographic images from the same patient. **(D)** Mid transesophageal long-axis view demonstrating a flail mitral cusp (*arrow*) along with severe mitral regurgitation on color Doppler. Three-dimensional images **(E)** also show the flail cusp along with **(F)** severe regurgitation.

a very useful complementary technique to assess leaflet motion in this setting. A rocking aortic PHV suggests a large dehiscence. However, in the mitral position, retention of the native valve leaflets can cause increased mobility of the prosthetic annulus and appear to be rocking. This "normal" situation can be differentiated from dehiscence by the absence of abnormal valvular regurgitation jets.[7] As listed in Table 2, additional extravalvular findings may be observed. These include microbubbles, sutures, strands, and masses. Although the presence of microbubbles and sutures are usually of no clinical significance, other findings, such as a thrombus, vegetation, or an abscess, require treatment.[9-11]

## Doppler Evaluation of Transvalvular Flow

### *Spectral Doppler*

**Transvalvular Gradient.** Blood velocity across a PHV is determined by several factors, including flow, valve size, and type.[7] Almost all PHVs produce some degree of obstruction to blood flow, and the degree of the obstruction considered normal depends on the type of prosthesis used. The least amount of obstruction is usually seen with stentless bioprostheses, pulmonary autografts, and homografts.[3] Accurate gradient measurements are best obtained by positioning the ultrasound probe as parallel as possible to the corresponding valvular flow. The simplified Bernoulli equation is used to calculate the peak pressure gradient across the valve, $\Delta P = 4 \times V^2$ (V = jet velocity in m/s) along with the mean gradient calculated from the valve velocity time integral (VTI), whether diastolic for mitral and tricuspid prostheses or systolic for aortic and pulmonic prostheses (Figures 1, 4, and 5). For bioprostheses, pressure gradients obtained by Doppler have been found to correlate well with those obtained invasively; however, for mechanical valves, results have been mixed; some studies have demonstrated good correlation[12] whereas others have reported substantial overestimation by Doppler.[13] Underestimation of pressure gradients usually occurs when the Doppler beam and the jet are improperly aligned; overestimation can occur if the velocity proximal to the lesion is high and neglected (such as in discrete subaortic stenosis or systolic anterior motion of the mitral valve)[14] and in the cases of smaller valves and high cardiac output. High transvalvular gradients are caused by a variety of factors, such as valve obstruction, high stroke volume (due to valvular regurgitation, a slow heart rate, or increased cardiac output associated with high output states such as anemia, fever, thyrotoxicosis), and patient–prosthesis mismatch (PPM)—when the implanted prosthesis is relatively small for the patient's body size.

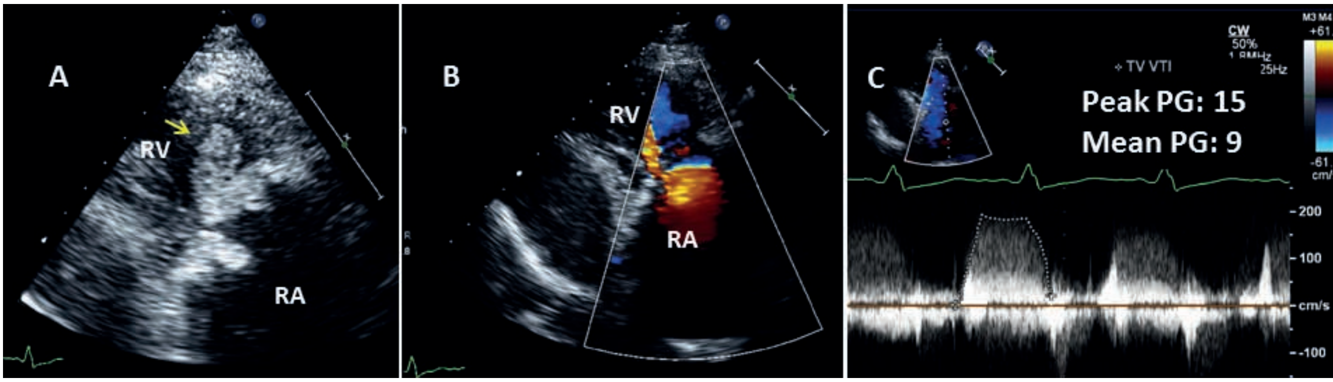



Figure 4. Bioprosthetic tricuspid valve stenosis and mass. Transthoracic echocardiographic images in the right ventricular outflow view demonstrating a bioprosthetic tricuspid valve with thickened leaflets along with a mobile mass present on the leaflets (*arrow*) suggestive of a vegetation or thrombus (A). (B) Color Doppler demonstrates turbulent diastolic flow across the valve. (C) Spectral Doppler confirms a peak E velocity of 2 m/s, a peak pressure gradient of 15 mm Hg, and a mean pressure gradient of 9 mm Hg consistent with severe stenosis. RA, right atrium; RV, right ventricle.

**Effective Orifice Area.** The continuity equation is used to calculate the effective orifice area (EOA). The EOA = stroke volume/VTI (using the PHV VTI). For mitral valves the EOA is calculated using the stroke volume measured in the left ventricular outflow tract (LVOT) (assuming that there is no significant aortic regurgitation). The simplified VTI ratio (VTI proximal to the valve/VTI distal to the valve) can be used avoiding the use of LVOT measurements; this is referred to as the dimensionless valve index (DVI). For assessment of mitral valve prostheses $DVI = VTI_{MV}/LVTI_{LVOT}$, and for aortic valve prostheses $DVI = VTI_{LVOT}/LVTI_{AV}$.[7] For aortic valves the DVI is not affected by either high output states or regurgitation, as the high flow will occur through both the prosthetic valve and the LVOT. However, for mitral valves, although the DVI is not affected by high output states, the DVI ratio can be elevated without significant stenosis when there is valvular regurgitation.[15] This method has not been validated for pulmonic and tricuspid prostheses.

**Early Velocity and Pressure Half Time.** Other Doppler parameters used for evaluation of the mitral valve include the early (E) diastolic filling velocity and the pressure half-time (PHT). The E velocity is a straightforward measurement that can provide a simple screening tool for valvular function. Normal values are usually $< 1.9$ m/s and elevated values can suggest the presence of either stenosis, regurgitation, or increased transmitral flow (high cardiac output).[6] The PHT method evaluates the rate of blood flow across the mitral valve and the time necessary for the transvalvular gradient to decline to half of its initial value. Prolongation of the PHT can suggest mitral valvular stenosis or obstruction. However, as this measurement is affected by multiple factors, such as left atrial and ventricular compliance, ventricular relaxation, and various states affecting the diastolic filling period, it can only serve as a possible clue to the presence of obstruction, which needs to be ascertained with other parameters.[7]

### *Color Flow Doppler*

The use of TTE with color Doppler is recommended for the initial evaluation of the presence of valvular regurgitation. As shown in Figures 3 and 6, the mitral prosthesis causes acoustic shadowing in the left atrium. This can obscure evidence of valvular regurgitation; thus, TEE, which provides more precise images, is usually needed to delineate the location and severity of valve regurgitation. This is especially true for paravalvular regurgitation jets (Figure 7).[4] Furthermore, TEE and 3D TEE in particular can better define the underlying cause of regurgitation, especially in the presence of a mechanical mitral valve prosthesis.[16,17]

Mechanical PHVs have some degree of physiologic transvalvular regurgitation.[18,19] PHV flow is divided into two components: backward flow, which occurs during valve closure, and closure backward flow, which occurs after the valve has already closed. This physiologic regurgitation of prosthetic valves rarely exceeds 10% of the forward flow[20] and is usually visualized as a narrow, laminar color jet of a short duration.[19] The number and location of regurgitant jets varies among the different valves and prostheses types. Although in mechanical monoleaflet valves the flow is usually eccentric, in bileaflet valves the flow is composed of three separate jets (Figure 8). Unlike mechanical PHVs, biological PHVs do not have a normal closing backward flow. Physiologic regurgitant jets are usually limited, low-velocity, nonaliasing, and rather homogenous upon color Doppler evaluation, in comparison with pathologic regurgitant jets, which are usually extensive, turbulent, and often eccentric.[21]

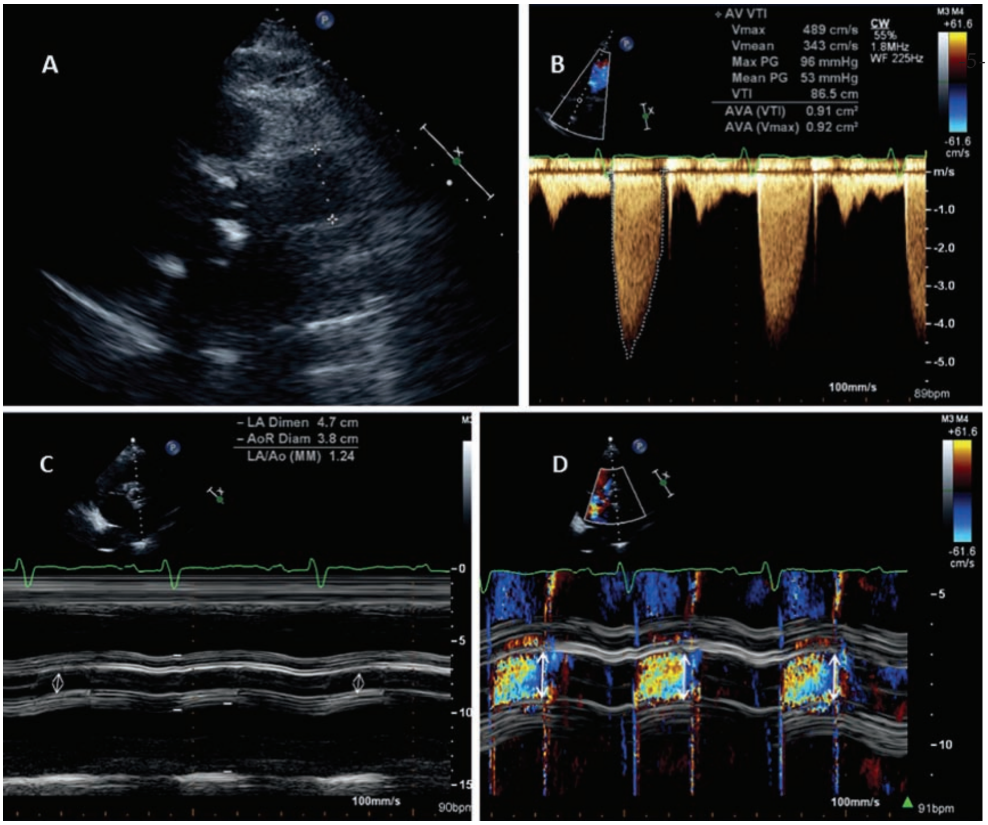
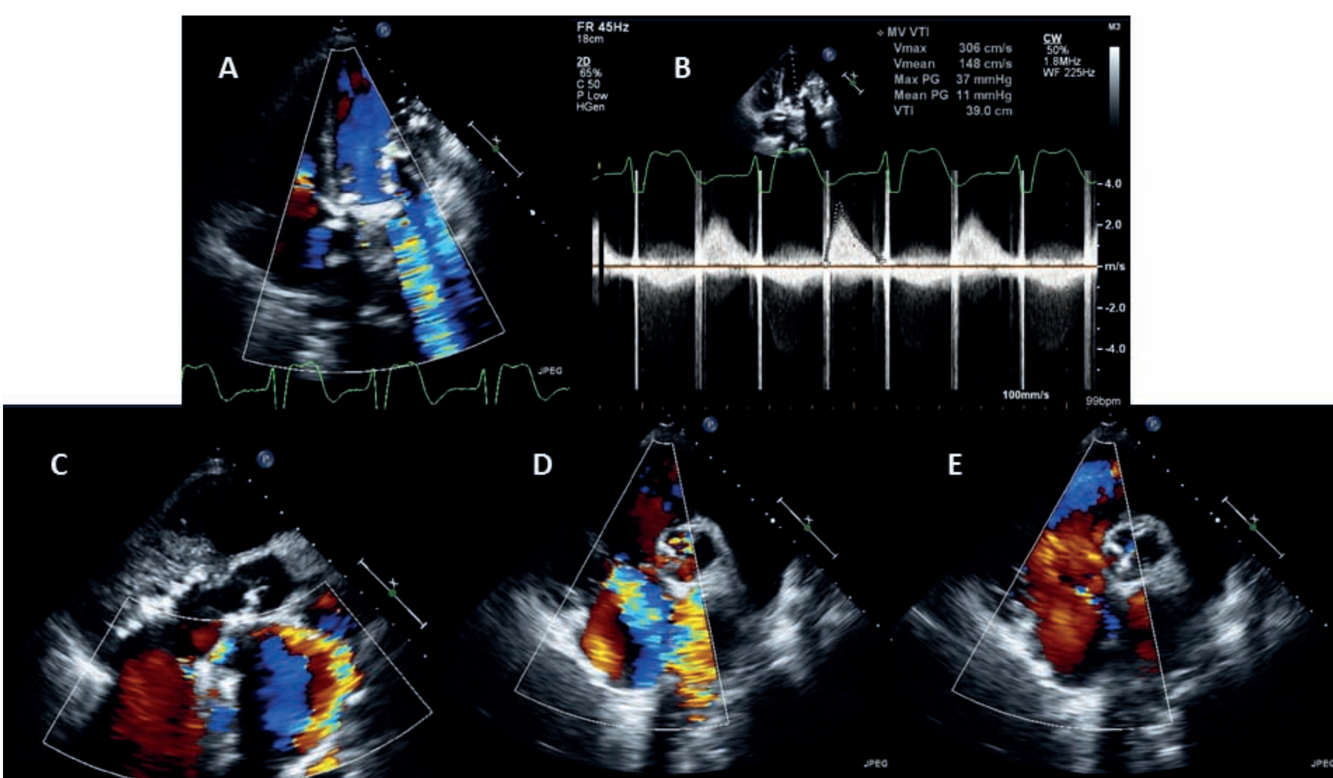



**Figure 5.** Elevated aortic pressure gradients across a bioprosthetic valve. This patient with a body surface area of 1.35 m$^2$ had a 19-mm bioprosthetic Mitroflow (SORIN S.p.A., Milan, Italy) valve implanted in the aortic position. Postoperative echocardiography demonstrated **(A)** an aortic root diameter of 2.95 cm on the parasternal long-axis view. **(B)** Peak pressure gradient across the valve was 96 mm Hg, with a mean gradient of 53 mm Hg. The valve itself was not adequately visible with transthoracic echocardiography due to acoustic shadowing from the valve; however, on M-mode echocardiography there was adequate opening of the valve (*double arrows*), also demonstrated on color M-mode echocardiography. Thus, the differential diagnosis was patient–prosthesis mismatch or elevated Doppler estimated pressures due to the pressure recovery phenomenon. Using the algorithm in Table 7 and Supplemental Appendix A, the patient received the appropriate sized valve. Thus, the elevated gradients are due to the pressure recovery phenomenon associated with aortic roots < 3 cm in diameter.

**Figure 6.** Two-dimensional transthoracic echocardiography showing a prosthetic mechanical St. Jude (St. Jude Medical, Secaucus, NJ) mitral valve and echocardiographic evidence of severe paravalvular leak. **(A)** In the four-chamber view there is severe acoustic shadowing making it impossible to assess the severity of the regurgitation from the mitral prosthesis. **(B)** Spectral Doppler through the valve demonstrates an increased diastolic mean pressure gradient of 11 mm Hg and a peak pressure gradient of 37 mm Hg without evidence of severe regurgitation going through the valve. **(C)** In the parasternal long-axis view, there is a wall-hugging, anterior, eccentric regurgitation jet consistent with severe mitral regurgitation. It is also seen in the short-axis view during systole **(D)**, disappearing in diastole **(E)**.



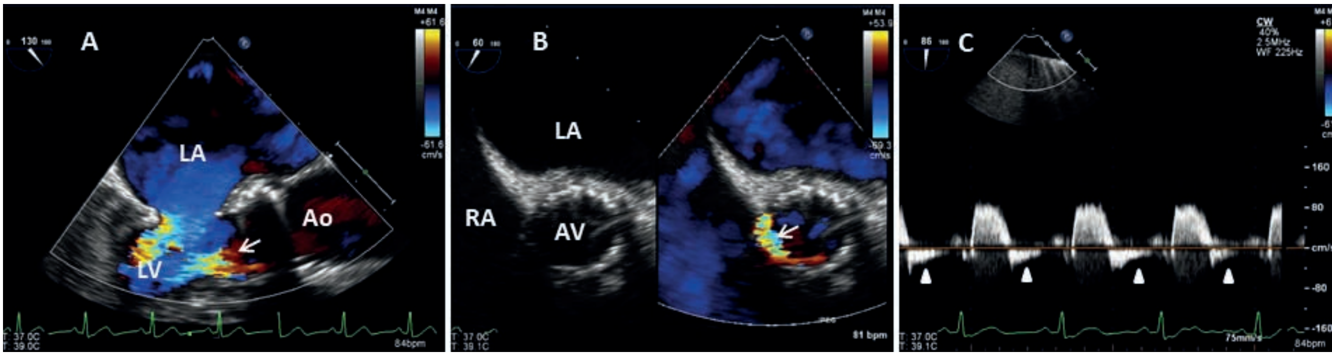



**Figure 7.** Severe paravalvular regurgitation after transcatheter aortic valve replacement. Transesophageal echocardiography performed immediately after valve deployment demonstrates severe paravalvular regurgitation (*arrow*) as seen on the long-axis view **(A)** which shows an eccentric jet. On the short-axis view **(B)** the two-dimensional image of the prosthetic valve ring is shown on the *left;* on the *right,* color Doppler shows the regurgitation jet (*arrow*) originating from around the valve on the anteroseptal territory consisting of > 20% of the valve ring, suggesting severe paravalvular regurgitation. **(C)** Flow reversal (*arrowhead*) is shown in the descending aorta, also consistent with severe aortic regurgitation. Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium.

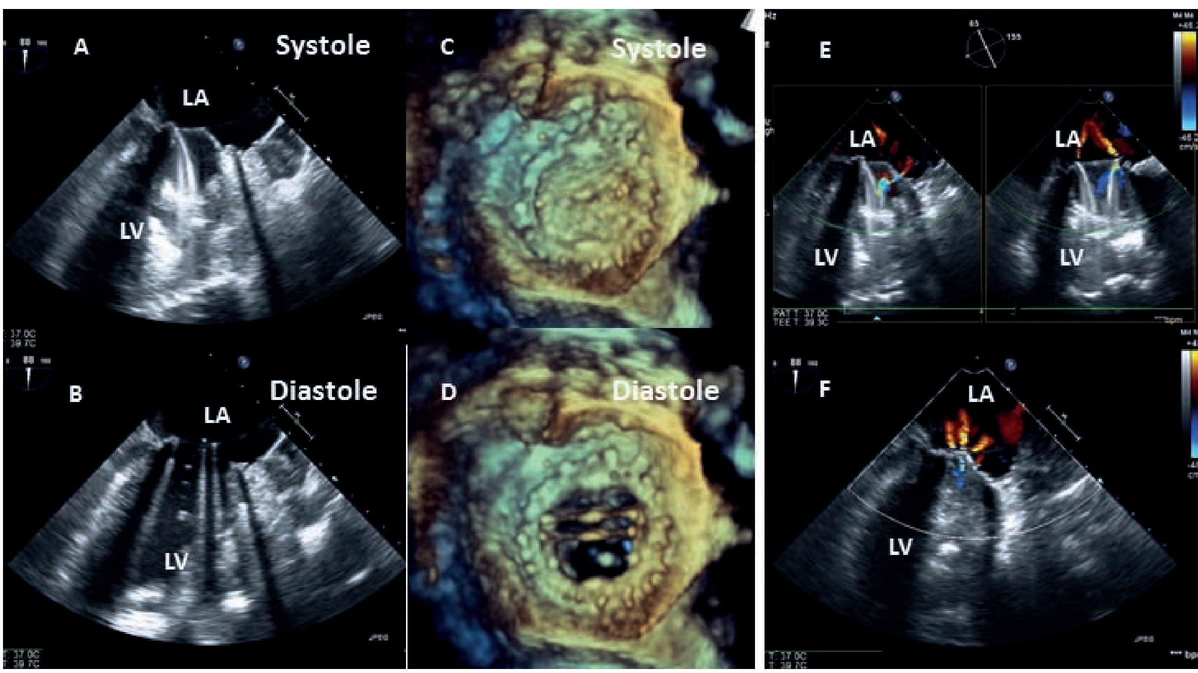



**Figure 8.** A normal functioning St. Jude (St. Jude Medical, Secaucus, NJ) mechanical mitral prosthesis. Transesophageal echocardiographic images of a normal functioning St. Jude mechanical mitral valve prosthesis demonstrating normal opening during diastole and closing during systole, seen both on two-dimensional **(A & B)** and three-dimensional **(C & D)** imaging. **(E & F)** Using color Doppler normal physiologic regurgitation jets are seen. Depending on the angle obtained, either two jets **(E)** or three jets **(F)** can be seen. Note the extensive shadowing caused by the mechanical valve on the two-dimensional images. LA, left atrium; LV, left ventricle.

The occurrence of leaks outside the suture ring is indicative of a paravalvular leak. These leaks are considered abnormal and can be a relatively common Doppler finding after insertion of surgical aortic prostheses; most remain unchanged within a 5-year follow-up period.[22] Paravalvular leaks are more common in older individuals and those with more severe aortic and mitral annular calcification. Paravalvular leaks have become one of the most common findings after transcutaneous aortic valve replacement.[23] Although most of these leaks after transcutaneous aortic valve replacement are not severe, even a moderate paravalvular leak has an adverse effect on survival and quality of life due to the development of congestive heart failure, anemia due to hemolysis, and clinical deterioration.

## Echocardiographic Evaluation for Prosthetic Valvular Dysfunctions

Doppler echocardiographic evaluation of PHVs should assess the following: (1) the seating of the valve, (2) the presence of any rocking motion, (3) the functioning of the prosthetic disks or cusps, (4) the presence of any visible extrinsic masses on or around

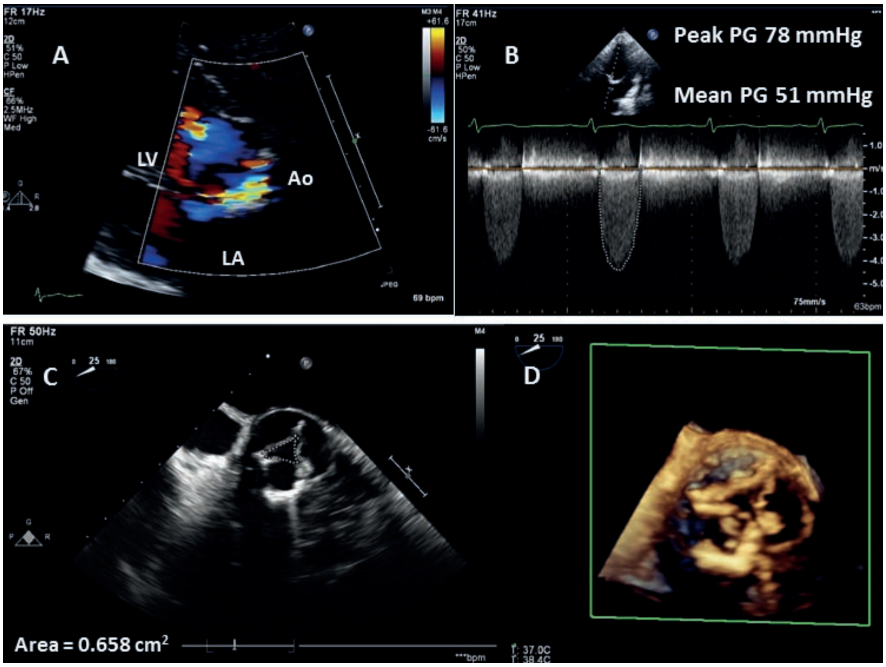



**Figure 9.** Degenerative bioprosthetic aortic valve with severe aortic stenosis and regurgitation. Transthoracic echocardiography demonstrating an eccentric jet **(A)** of aortic regurgitation during diastole along with an increased systolic pressure gradient across the aortic valve with a round contour (peak pressure gradient of 78 mm Hg and a mean pressure gradient of 51 mm Hg) **(B)** which is consistent with severe aortic stenosis. There was also severe aortic regurgitation (with diastolic flow reversal in the descending aorta, not shown here). On transesophageal echocardiography in the short-axis view **(C)** there is restricted opening of the valve cusps with a planimetered valve area of 0.66 $cm^2$ and leaflet thickening on three-dimensional transesophageal echocardiography **(D)**. Ao, aorta; LA, left atrium; LV, left ventricle.

the prosthesis, (5) any evidence of valvular regurgitation, and (if present) the severity, and (6) any evidence of valvular stenosis, and (if present) the severity. If valve dysfunction is identified, the responsible mechanism or mechanisms, as detailed in Table 3A, should be determined.

### *Aortic Prosthesis Evaluation*

**Aortic Stenosis/Obstruction.** A detailed examination of the prosthetic aortic valve should include a visual assessment, in addition to evaluation of pressure gradients, the presence of regurgitation, and assessment of surrounding structures, such as the left ventricle, aorta, and left atrium (Table 3B). TTE is used for the initial evaluation of the presence of stenosis or regurgitation, as well as to assess hemodynamics. TEE is recommended for the identification of valve thrombosis and to assess thrombus size and mobility. Doppler measurements should be obtained from multiple views for the best-aligned signal and to reduce angle error. The envelope of normal prosthetic Doppler gradients is similar to those obtained from patients with mild native aortic valve stenosis, demonstrating a triangular contour with an early to mid-peaking gradient; the gradients are generally low with maximal velocities $< 2$ m/s. In the presence of a more significant stenosis there is a rise in Doppler velocities, gradients, and VTI along with a more delayed peaking of the velocity jet, the acceleration time, and the acceleration time/ejection time ratio,[24] giving it a rounded contour, as seen in Figure 9. However, elevated velocities and gradients can be found in several situations in which the valve is not stenosed, such as PPM, high output states, significant aortic regurgitation, or in the presence of an obstructive thrombus or vegetation.[7] In addition, high-velocity, turbulent blood flow can result in an unreliable high transvalvular pressure gradient measurement that does not reflect actual gradients across the valve and the EOA. This phenomenon, termed *pressure recovery,* is more common with bileaflet mechanical valves and results in a high velocity across the prosthesis. Care should be taken to differentiate this from valvular stenosis or for PPM, as shown in Figure 5.[4,7] Conversely, as is the case with native valves, a significant stenosis can be present in the setting of low gradients if there is a decreased stroke volume. The EOA and DVI are additional complementary quantitative parameters that are less flow dependent. The EOA obtained by echocardiography correlates well with that obtained invasively.[25] However, it is dependent on the specific implanted valve size, and, as such, should be referenced according to the type of valve being evaluated. When the calculated EOA is $< 0.8$ $cm^2$, it is considered significant stenosis for any valve type. Pitfalls with the use of EOA mainly consist of incorrect measurements of the LVOT and the noncircular shape of the LVOT. As the DVI represents a dimensionless index it is less dependent on valve size and LVOT measurements and, therefore, is a helpful tool for screening for valve dysfunction.[26] A DVI $< 0.25$ is highly suggestive of significant valvular obstruction.[7,26,27] The more abnormal the evaluated parameters, the more likely that there is significant obstruction. However, it is important to differentiate true valvular stenosis from prevalvular obstruction caused by systolic anterior motion of the mitral valve, obliteration of the left ventricular (LV) cavity during systole, or a subaortic membrane. Figure 10 details a suggested protocol for the evaluation of patients with an elevated aortic jet velocity.

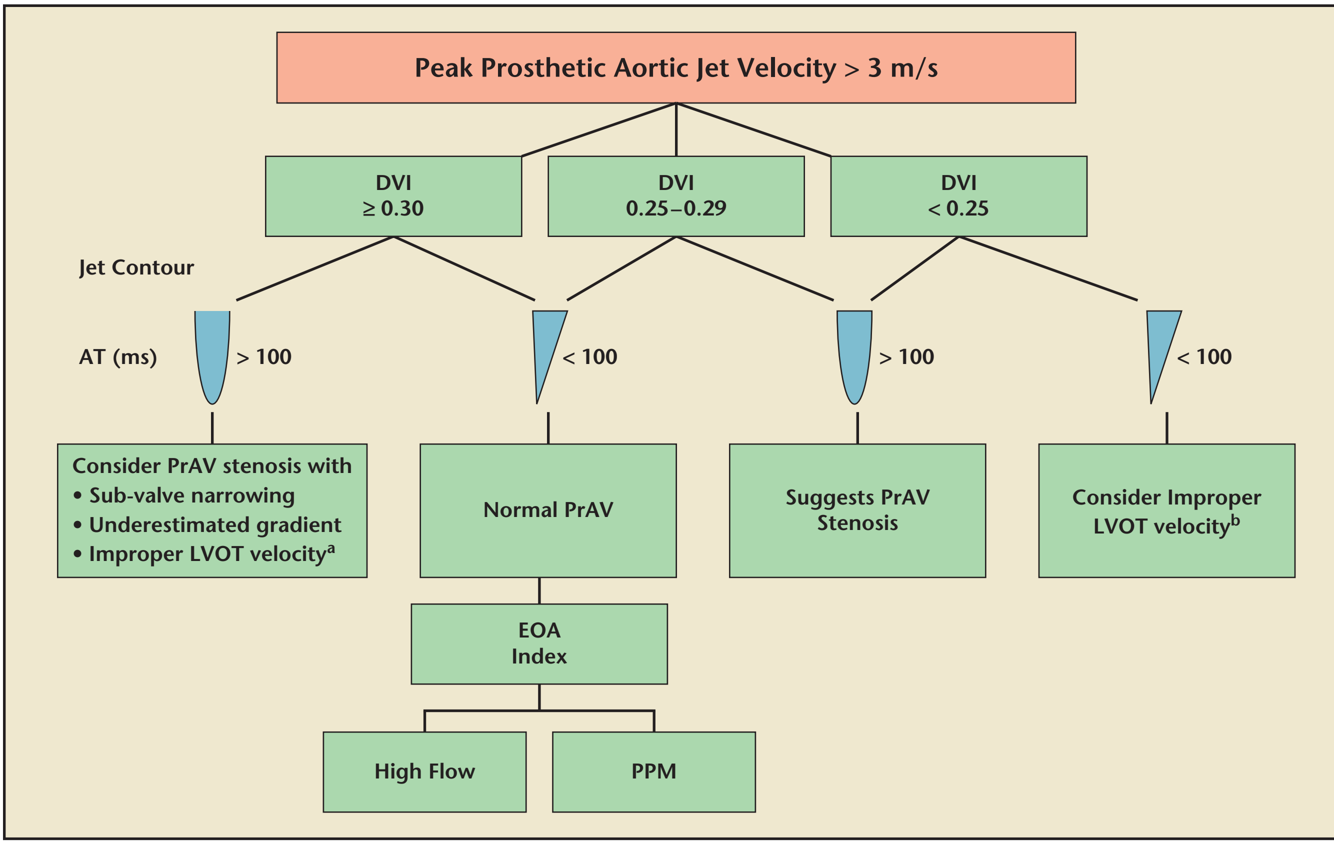



**Figure 10.** Algorithm for evaluation of elevated peak prosthetic aortic jet velocity incorporating DVI, jet contour, and AT. [a]When the pulsed-wave Doppler sample in the LVOT is too close to the aortic valve $V_1$ will be elevated and lead to erroneous results (particularly when jet velocity by continuous-wave Doppler is ≥ 4 m/s). [b]When the pulsed-wave Doppler sample in the LVOT is too far away from the valve (too apical) inaccurate assessment of the aortic valve stenosis can also occur (particularly when jet velocity is 3-3.9 m/s). Stenosis further substantiated by EOA derivation compared with reference values if valve type and size are known. Fluoroscopy and TEE are helpful for further assessment, particularly in bileaflet valves. AT, acceleration time; AVR, aortic valve replacement; DVI, dimensionless valve index; EOA, effective orifice area; LVOT, left ventricular outflow tract; PPM, patient–prosthesis mismatch; PrAV, prosthetic aortic valve; TEE, transesophageal echocardiography. Reprinted with permission from Zoghbi WA et al.[7]

**TABLE 3A**

**Different Etiologies for Prosthetic Valve Dysfunction**

| Structural | Nonstructural |
|---|---|
| Intrinsic valvular abnormalities | Thrombosis |
| - Degeneration and wear | Pannus formation |
| - Valve fracture | Paravalvular leak |
| - Disc dysfunction | Hemolysis |
| | Endocarditis |
| | Valve dehiscence |
| | Patient–prosthesis mismatch |

**Aortic Regurgitation.** A multiparameter approach is used to assess the degree of aortic regurgitation. Color and spectral Doppler as well as LV chamber size are used. Regurgitation can be divided into valvular and/or paravalvular regurgitation. Color Doppler interrogation of the aortic valve prosthesis and its surrounding ring is the first step in the evaluation for the presence of prosthetic aortic regurgitation. Multiple views, including the parasternal long and short axis, and the apical four- and five-chamber views, along with any additional off-axis view that might provide additional input, are used. In general, the ratio of jet diameter/LVOT diameter is used for classification of the severity of prosthetic aortic regurgitation with a ratio of > 25% considered more than mild.[22] This is most applicable for central jets, but it is problematic in the presence of aortic regurgitation eccentric jets that can impinge on the ventricular wall and appear less impressive on color Doppler, as shown in Figure 7. Because the valvular prosthesis produces shadowing, this can obscure evidence of valvular regurgitation when using TTE; therefore, TEE can provide superior images, especially when using multiplane imaging.[28] For paravalvular regurgitation, approximation of the area of the sewing ring involved in the

**TABLE 3B**

**Evaluation of Aortic Prosthetic Valve Dysfunction**

| **Stenosis** | | | |
|---|---|---|---|
| **Criteria** | **Comments** | | |
| Elevated pressure gradients across the AV<br>Elevated jet velocity (> 3 m/s)<br>Delayed peak of the velocity jet<br>Prolonged AT (< 100 ms probably normal)<br>Prolonged ET<br>Increased AT/ET (> 0.4) | Rule out obstructive thrombus, patient–prosthesis mismatch, high-output states, pressure recovery phenomenon (due to a small aortic root or ascending aorta), and significant aortic regurgitation; inhomogeneous flow profiles, especially in mechanical valves, can lead to falsely elevated measurements[14]; gradients may be elevated in normal bileaflet mechanical valves due to pressure recovery at the valve level[7];<br>Rule out the obstruction originates at the valve level and not due to systolic anterior motion of the mitral valve, cavity obliteration, or subaortic membrane | | |
| Decreased calculated EOA (< 0.8 $cm^2$ considered significant) | Should be referenced with the implanted valve size | | |
| DVI (< 0.3 suggests obstruction, < 0.25 suggests significant stenosis) | A falsely low DVI can occur in the presence of subvalvular stenosis<br>EOA and DVI are not affected by high flow conditions and regurgitation | | |
| **Regurgitation** | | | |
| **Criteria** | **Comments** | | |
| Evaluate for valve dehiscence, presence of thrombus or vegetation, leaflet degeneration | | | |
| **Color Doppler:**<br>For paravalvular regurgitation: assess the area of the sewing ring involved in the parasternal short-axis view on TTE or short-axis view on TEE (< 10% = mild, 10% to 20% = moderate, > 20% = severe) | Pathologic regurgitation usually turbulent and extensive<br>Should be measured in the parasternal long-axis view<br>Eccentric jets might underestimate severity of regurgitation | | |
| VTI ratio (forward flow VTI/back flow VTI ≤ 1 signifies severe AR) | LVOT VTI should be acquired not too close to the valve prosthesis as this can lead to overestimation of VTI due to proximal acceleration and, thus, overestimation of regurgitation | | |
| **General parameters for evaluation and grading of AR[7]:** | **Mild** | **Moderate** | **Severe** |
| Regurgitation jet width (%) | ≤ 25 | 26-64 | ≥ 65 |
| Jet density | Incomplete | Dense | Dense |
| Flow reversal in descending aorta | Absent | Partial | Holodiastolic |
| Regurgitant volume (mL/beat) | < 30 | 30-59 | ≥ 60 |
| Regurgitant fraction (%) | < 30 | 30-50 | ≥ 50 |
| Pressure half time[b] (ms) | > 500 | 200-500 | < 200 |

[a]It should be taken into considerations that LV volumes can reflect the preoperative state in some patients; however these should decrease with time.
[b]Poor agreement, limited utility, can be affected by other variables, such as left ventricular compliance.
AR, aortic regurgitation; AT, acceleration time; AV, aortic valve; DVI, dimensionless valve index; EOA, effective orifice area; ET, ejection time; LVOT, left ventricular outflow tract; TEE, transesophageal echocardiography; TTE, transthoracic echocardiography; VTI, velocity time integral.

short-axis view can provide a semi-quantitative measurement for the severity: < 10% suggests mild, 10% to 20% suggests moderate, and > 20% suggests severe paravalvular regurgitation. Although current guidelines recommend the use of the pressure half-time method,[7,29] it is our experience that it is most useful in identifying acute and very severe aortic regurgitation, but otherwise the pressure half-time method often lacks diagnostic accuracy and is therefore recommended only as a complementary tool for other diagnostic methods.

### *Mitral Prosthesis Evaluation (Table 4)*

**Mitral Stenosis/Obstruction.** The normal mitral valve area is 4 to 6 $cm^2$. Prosthetic mitral valves have a smaller cross-sectional area and are thus inherently obstructive. Mechanical mitral prostheses have a larger EOA as compared with bioprostheses.[30] As the EOA and pressure gradients vary among prostheses, it is crucial to know the type of implanted valve, along with established data regarding its normal parameters[6] in order to determine if it is functioning properly (Supplemental Appendix B). Visualization of severely thickened bioprosthetic cusps, with or without reduced mobility, can suggest the presence of valve stenosis or obstruction. This should be assessed with spectral Doppler as well. Finding an increased E filling velocity (> 1.9 m/s) along with elevated pressure gradients across the valve (> 6 mm Hg) indicates that there is stenosis (as shown in Figure 2). Although a PHT of < 130 ms is considered normal in most cases,[30] more prolonged values (> 200 ms) are suggestive of valvular obstruction. EOA calculation is not routinely used and usually reserved for those cases in which there is a discrepancy among other parameters. The PHT method has only been validated for native mitral valves[31]; used in prosthetic mitral valves, the EOA may be overestimated.[30,32,33] EOA calculation should be done using the continuity equation as previously described. As the mitral valve VTI is less dependent on heart rate (especially in tachycardia and bradycardia states, in which gradients can be misleading) using the DVI (ie, the VTI ratio of the $MV_{VTI}/LVOT_{VTI}$) can produce an index for prosthetic valve function. This has been evaluated primarily for mechanical mitral prosthesis. A ratio of < 2.2 is often normal, and higher values warrant further evaluation for prosthesis dysfunction. The DVI can be elevated in the presence of stenosis as well as in other high-output states, and with increased mitral flow due to mitral regurgitation.[15]

Abnormal Doppler parameters may be due to true abnormalities reflecting valve dysfunction, or other clinical factors, such as the patient's BSA, hemodynamic status, and the presence of a high output state (eg, thyrotoxicosis, anemia, arteriovenous fistula). The normal echocardiographic Doppler values for the implanted valve should be reviewed; comparison of the current echocardiographic Doppler findings with the baseline parameters obtained immediately after valve implantation and during subsequent studies is very useful.

**Mitral Regurgitation.** Detection and assessment of mitral regurgitation severity with the use of color Doppler can sometimes be difficult due to shadowing and artifacts from the valve prosthesis, especially in the presence of mechanical valves, as shown in Figures 2 and 7. TEE is highly sensitive and specific for the evaluation of mitral valve prostheses regurgitation, and is also helpful in evaluating its mechanism. Sufficient data for clinical decision making can generally be obtained when combing TTE along with 2D and 3D TEE evaluation. Using 3D TEE the mitral valve can be visualized through an en-face surgical view, which is optimal for determining prosthetic valve function and morphology, and for defining and localizing paravalvular regurgitation (Figure 3).[34] Because valvular regurgitation can be present either through the valve itself or through the prosthetic mitral ring causing paravalvular regurgitation, multiple views should be assessed in order to determine the exact origin of regurgitation. Assessing the severity of mitral regurgitation also requires a multiparameter approach, similar to those used for native valves. These parameters, detailed in Table 4, include the following: continuous wave flow jet contour and density, E wave velocity, LV morphology, vena contracta width, the regurgitant volume and fraction, pulmonary venous flow, color flow area, and 3D assessment. The multiparameter approach is particularly relevant for mechanical mitral prostheses, in which paravalvular jets are more common, making quantification more difficult.[35]

In a patient with a mechanical mitral valve prosthesis, the presence of an E velocity < 1.9 m/s, a DVI ratio < 2.2, and a PHT < 130 ms signifies a normal functioning prosthetic valve, whereas in the presence of an E velocity ≥ 1.9 m/s, a DVI ratio > 2.2, and a PHT < 130, the primary concern would be that there is significant mitral regurgitation, which can be missed or underestimated on TTE due to shadowing of the prosthetic valve.[30,36]

### *Pulmonic Prosthesis Evaluation (Table 5)*

**Pulmonic Valve Stenosis.** It is often difficult to visualize and evaluate the pulmonary valve due to its anterior and superior location in

## TABLE 4

### Evaluation of Mitral Prosthetic Valve Dysfunction

**Stenosis**

| **Criteria** | **Comments** |
|---|---|
| Visualization of severely thickened MV cusps, or restricted motion of MV cusps | Acoustic shadowing can prevent adequate visualization |
| E velocity: ≥ 1.9 m/s suspicious; > 2.5 m/s highly suggestive | Can be elevated in hyperdynamic states, regurgitation, and PPM; for some valves an E of up to 2.4 m/s can be normal for mechanical valves[6,7,15,48] |
| Mean gradient: > 5-6 mm Hg = suspicious; > 10 mm Hg = indicative of significant stenosis | Mean values of 10-12 mm Hg have been reported in normal functioning Starr-Edwards and St. Jude[a] bileaflet valves, respectively[7] High gradients can be due to tachycardia, hyperdynamic states, regurgitation, or PPM in the absence of stenosis |
| Pressure half time: > 130 ms = suspicious; > 200 ms = highly suggestive of stenosis | Should not be obtained in patients with AV block, tachycardia, or any other condition in which there is a short diastolic filling period or the E and A waves are merged[7]; cannot be used to calculate the EOA of prosthetic valves |
| EOA = SV/ $MV_{VTI}$: > 2 $cm^2$ = suggestive; > 1 $cm^2$ = highly suggestive of stenosis | Assess compared to specific prosthesis normal values[6]; SV calculation can be misleading and is prone to error |
| DVI = $MV_{VTI}/LVOT_{VTI}$: > 2.2 = suggestive; > 2.5 = highly suggestive of stenosis | Higher in bioprosthesis compared with mechanical prostheses[7,30]; can be elevated in the presence of other high-output states including MR |

**Regurgitation**

| **Criteria** | **Comments** |
|---|---|
| Visualization using 2D and 3D -Cusp morphology, presence of rupture, excessive motion ("rocking") of the sewing ring -Left ventricular structure: usually dilated in the presence of severe MR | Visualization can be impaired due to shadowing and artifacts from the prosthesis |
| Color Doppler evaluation | Eccentric jets might underestimate severity of regurgitation (Coanda effect); if such eccentric jet extends to the posterior atrial wall—probably severe regurgitation |
| E velocity: ≥ 1.9 m/s | Can be elevated in hyperdynamic states, stenosis, and patient–prosthetic mismatch |
| DVI = $MV_{VTI}/LVOT_{VTI}$: > 2.5 | Similar values can be obtained in the presence of stenosis/obstruction and other high output states |

| **General parameters for evaluation and grading of MR[7]** | **Mild** | **Moderate** | **Severe** |
|---|---|---|---|
| Color Doppler: jet area[b] | < 20% | | > 40% |
| Doppler continuous-wave jet density | Faint | Dense | Dense |
| Doppler continuous-wave jet contour | Parabolic | Usually parabolic Systolic dominant[c] | Early peaking, triangular |
| Pulmonary vein flow | Systolic blunting[c] | Systolic blunting | Systolic flow reversal |
| Vena contracta width (cm) | < 0.3 | 0.3-0.59 | ≥ 0.6 |
| Regurgitant volume (mL/beat) | < 30 | 30-59 | ≥ 60 |
| Regurgitant fraction (%) | < 30 | 30-49 | ≥ 50 |
| Effective regurgitant orifice area[d] | < 0.2 | 0.2-0.49 | ≥ 0.5 |

[a]Starr-Edwards valves are manufactured by Edwards Lifesciences (Irvine, CA); St. Jude valves are manufactured by St. Jude Medical (Secaucus, NJ).
[b]Due to acoustic shadowing, TTE is often inadequate to assess color flow jet area and a TEE is needed for adequate evaluation of jet area.
[c]Unless there are other reasons to cause systolic blunting (such as elevated left atrial pressure or atrial fibrillation).
[d]As in most patients with MV prosthesis the regurgitant jet is mostly eccentric, the effective regurgitant orifice area is usually overestimated and thus values for severe prosthetic valve MR are ≥ 0.5.[7,35]
AV, atrioventricular; DVI, dimensionless valve index; EOA, effective orifice area; LVOT, left ventricular outflow tract; MR, mitral regurgitation; MV, mitral valve; PPM, patient–prosthetic mismatch; SV, stroke volume; TEE, transesophageal echocardiography; TTE, transthoracic echocardiography; VTI, velocity time integral.

the right ventricular outflow tract. Problems with imaging and measuring the correct right ventricular outflow tract diameter, which changes in size as it gets closer to the pulmonary valve, substantially compromise the reproducibility and accuracy of right-sided cardiac output determinations, and the estimation of the EOA.[7] Valve cusps should be assessed for the presence of leaflet thickening or immobility. Doppler evaluation should include evaluation of the peak velocity across the valve along with the peak and mean pressure gradients. The right ventricle and atrium should also be evaluated for the presence of hypertrophy, size, and function and compared with prior values. Most data available on prosthetic pulmonary valves are based on studies of pediatric patients. The data are mostly limited to assessment of pulmonary homografts and autografts[37,38] with very limited data regarding mechanical prostheses. A peak velocity < 2.5 m/s (mean gradient < 15 mm Hg) for a homograft or < 3.2 m/s (mean gradient < 20 mm Hg) for a xenograft are considered normal. Another assessment method is evaluation of the tricuspid regurgitation jet to estimate the RV systolic pressure which, if elevated, can warrant further evaluation for the presence of pulmonic valve stenosis.[7]

**Pulmonic Valve Regurgitation.** Evaluation of pulmonic regurgitation generally starts with the use of color Doppler. A jet of < 25% of the pulmonary annulus is considered mild, whereas a jet > 50% of the annulus is considered severe. This method is limited when encountering eccentric and paravalvular jets, which can cause underestimation of regurgitation. Reversal of flow in the distal main pulmonary artery, if obtainable, is indicative of at least moderate pulmonic regurgitation. The density of the pulmonic regurgitation signal also

**TABLE 5**

**Evaluation of Prosthetic Pulmonic Valve Dysfunction**

| Criteria | Comments |
|---|---|
| **Stenosis** | |
| Valve visualization for thickening and immobility | Pulmonic valves are placed in aberrant position and the presence of RV structural abnormalities can interfere with imaging, making standardization of Doppler parameters difficult |
| Peak velocity > 3 m/s suspicious for prosthetic and homograft pulmonic valve stenosis | |
| Impaired RV function and/or elevated RV systolic pressure | Rule out other causes for these findings |
| DVI, EOA | Theoretically possible but not validated in studies |
| **Regurgitation** | |
| Color flow: > 50% of pulmonary annulus suggests severe PR and/or the PR jet extends to the level of the tricuspid valve papillary muscles | Limited when encountering eccentric and paravalvular jets, as it can lead to underestimation |
| Regurgitant fraction > 50% | Theoretically possible but not validated in studies |
| Continuous-wave jet density: dense jet suggests at least moderate regurgitation | |
| Presence of diastolic flow reversal in the distal pulmonary artery suggests at least moderate regurgitation | |

DVI, dimensionless valve index; EOA, effective orifice area; PR, pulmonary regurgitation; RV, right ventricular.

**TABLE 6**

**Evaluation of Prosthetic Tricuspid Valve Dysfunction**

| **Stenosis** | | | |
|---|---|---|---|
| **Criteria** | **Comments** | | |
| Valve visualization for thickening and immobility | | | |
| Peak velocity > 1.7 m/s | | | |
| Mean gradient ≥ 6 mm Hg | | | |
| Pressure half time ≥ 230 ms | | | |
| **Regurgitation** | | | |
| **Criteria** | **Comments** | | |
| Color Doppler for qualitative estimation | Can sometimes be limited due to attenuation, especially in the presence of mechanical valves | | |
| **General parameters for evaluation and grading of MR(7):** | **Mild** | **Moderate** | **Severe** |
| Vena contracta ($cm^2$) | < 5 | 5-10 | > 10 |
| Doppler jet density and contour | Incomplete | Dense | Dense, triangular, early peaking |
| Hepatic vein systolic flow | Normal or blunted | Blunted | Blunted or reversal |

reflects the severity of regurgitation. Quantitative measures of pulmonic regurgitation severity such as regurgitation fraction are theoretically valid; however, they have not been validated in studies.[7] Other indirect signs may aid in the diagnosis, and include diastolic flattening and paradoxical motion of the interventricular septum due to volume overload.[39]

### *Tricuspid Prosthesis Evaluation (Table 6)*

**Tricuspid Valve Stenosis.** TTE allows for multiple views of the tricuspid valve, usually with good image quality due to its proximity to the anterior chest wall. Thickening or reduced motion of the valve cusps can suggest stenosis or valve obstruction. An increased E wave velocity > 1.7 m/s, an elevated mean pressure gradient > 6 mm Hg, or a PHT > 230 ms are consistent with tricuspid valve stenosis,[40,41] as shown in Figure 4. Currently, there are no data regarding EOA evaluation for prosthetic tricuspid valves. Other supporting indirect parameters include enlargement of the right atrium and a widened inferior vena cava.

**Tricuspid Valve Regurgitation.** Using TTE to determine the presence of tricuspid regurgitation can sometimes be limited due to attenuation, especially in the presence of mechanical valves. The valve is usually best evaluated in the right ventricular inflow, or subcostal views. Color Doppler allows for a qualitative estimate of regurgitation severity and its location. Additional parameters obtained by spectral Doppler can aid in the estimation of the amount of tricuspid regurgitation, and include jet density and contour, time of the peak of the tricuspid regurgitation jet velocity, and tricuspid peak and mean pressure gradients.[7] Additional indirect parameters include significant reversal or significant blunting of flow during systole in the hepatic veins by pulsed wave and color flow Doppler; however, although flow reversal is usually indicative of significant tricuspid regurgitation, systolic blunting can also appear in the presence of atrial fibrillation or in the presence of elevated right atrial pressure.[42]

### *Patient–Prosthesis Mismatch*

In some patients the implanted PHV is small in comparison with the patient's body size, resulting in inadequate blood flow to meet the metabolic demands of the patient,

**TABLE 7**

**Three Easy Steps to Avoid Patient–Prosthesis Mismatch**

**Step 1:** Calculate the patient's BSA using the formula:

$$BSA = ([weight_{kg}]^{0.425} \times [height_{cm}]^{0.725}) \times 0.007184$$

**Step 2:** Determine the minimal requirement for prosthetic valve EOA to avoid patient–prosthesis mismatch

| Patient BSA ($m^2$) | Minimal Valve EOA ($cm^2$) for Indexed EOA > 0.85 $cm^2/m^2$ (ideal) | Minimal Valve EOA ($cm^2$) for Indexed EOA > 0.80 $cm^2/m^2$ | Minimal Valve EOA ($cm^2$) for Indexed EOA > 0.75 $cm^2/m^2$ |
|---|---|---|---|
| 1.30 | 1.11 | 1.04 | 0.98 |
| 1.35 | 1.15 | 1.08 | 1.01 |
| 1.40 | 1.20 | 1.12 | 1.05 |
| 1.45 | 1.23 | 1.16 | 1.09 |
| 1.50 | 1.28 | 1.20 | 1.13 |
| 1.55 | 1.32 | 1.24 | 1.16 |
| 1.60 | 1.36 | 1.28 | 1.20 |
| 1.65 | 1.40 | 1.32 | 1.24 |
| 1.70 | 1.45 | 1.36 | 1.28 |
| 1.75 | 1.49 | 1.40 | 1.31 |
| 1.80 | 1.53 | 1.44 | 1.35 |
| 1.85 | 1.57 | 1.48 | 1.39 |
| 1.90 | 1.62 | 1.52 | 1.43 |
| 2.00 | 1.70 | 1.60 | 1.50 |
| 2.05 | 1.74 | 1.64 | 1.54 |
| 2.10 | 1.79 | 1.68 | 1.58 |
| 2.15 | 1.83 | 1.72 | 1.61 |
| 2.20 | 1.87 | 1.76 | 1.65 |
| 2.25 | 1.91 | 1.80 | 1.69 |
| 2.30 | 1.96 | 1.84 | 1.73 |
| 2.35 | 2.00 | 1.88 | 1.76 |
| 2.40 | 2.04 | 1.92 | 1.80 |
| 2.45 | 2.08 | 1.96 | 1.84 |
| 2.50 | 2.13 | 2.00 | 1.88 |

**Step 3:** Choose a prosthesis using reference values for EOA of different types and sizes of prostheses.

BSA, body surface area; EOA, effective orifice area.
Reprinted with permission from Pibarot and Dumesnil.[43]

even when the valve is functioning adequately.[4] This situation should be distinguished from intrinsic valvular obstruction/stenosis. PPM is more common in patients with aortic than with mitral valve prostheses and should be suspected in patients with small aortic (< 23 mm) or mitral (< 27 mm) valve prostheses and an average BSA ≥ 1.7 $m^2$. For aortic valves, PPM is considered mild if the EOA/BSA (EOA index) is > 0.85 $cm^2/m^2$, moderate if it is 0.65 to 0.85 $cm^2/m^2$, and severe if it is ≤ 0.65 $cm^2/m^2$. For mitral valves, PPM is considered mild if the EOA index is > 1.2 $cm^2/m^2$, moderate if it is 1.2 to 0.9 $cm^2/m^2$, and severe if it is ≤ 0.9 $cm^2/m^2$. The reported prevalence of PPM varies widely between reports from 19% to 70%.[43,44] An aortic PPM ≤ 0.85 $cm^2/m^2$ can be associated clinically with less symptomatic

**TABLE 8**

**Criteria Aiding in the Differentiation Between Thrombus and Pannus**

| Thrombus | Pannus |
|---|---|
| Occurs more often on the inflow side for atrioventricular valves (mitral and tricuspid) and on the outflow side for aortic and pulmonic valves | Occurs more often on the ventricular side |
| Occurs in an earlier period after valve implantation (can occur after weeks or months after implantation, but not exclusively) | Occurs at a later period after valve implantation (typically several months to years after) |
| History of inadequate anticoagulation therapy | |
| Recent history of stroke or other embolic phenomena | |

improvement after surgery, worse exercise cardiac hemodynamics, more cardiac events after operation, lesser regression of LV hypertrophy, with some reports suggesting a higher rate of short-term postoperative mortality.[44] As valves vary by design and manufacturer, estimates of maximal theoretical EOAs are required for each individual valve type and size to avoid the issue of PPM.[45] One suggested algorithm to select the most appropriately sized and available prosthesis to prevent aortic PPM is by calculating the patient's BSA and referring to the data in Table 7 and Supplemental Appendix A. This method has been mainly validated for aortic prostheses.[43]

### *Thrombus Versus Pannus*

Thrombus formation is a major complication especially associated with, but not limited to, patients with mechanical PHVs. Thrombus formation is also not rare in patients with bioprosthetic tricuspid valves. The estimated annual incidence of PHV thrombus formation is reported to be up to 0.4% in those with mechanical valves, and higher in those with mitral valves than with aortic prostheses.[46,47] The presence of a thrombus can cause serious complications, such as thromboemboli or interference with normal valve function, causing either stenosis, regurgitation, or both. A finding suspicious for thrombus must be differentiated from pannus tissue, which usually originates from the neointima and consists of myofibroblasts and extracellular matrix molecules such as collagen. Based solely on echocardiographic findings, it can be hard to differentiate between the two entities, which can also coexist. Several other parameters, as described in Table 8, can aid in this differentiation which is clinically important for adequate therapeutic decision making.

## Conclusions

Comprehensive and diagnostic evaluation of prosthetic heart valves should thoroughly assess several factors. It is important to have knowledge about the specific type and size of valve when assessing prosthetic valves by Doppler echocardiography, as valve type and size may affect their characteristics. As the assessment of PHVs can be complex and challenging, it may lead to diagnostic dilemmas. Use of TTE, and 2D and 3D TEE, in addition to a thorough examination of the valve structure, leaflet motion, and color, as well as spectral Doppler imaging, is essential. ■

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## MAIN POINTS

- As with native valve disease, prosthetic heart valve (PHV) dysfunction may manifest with acute clinical findings, have progressive chronic deterioration, or be asymptomatic. Echocardiography is the initial and most widely used imaging modality for evaluation of PHVs and screening for PHV dysfunction.
- Data regarding the date of surgery, type and size of valve implanted, along with the patient's heart rate, blood pressure, height, weight, and body size, facilitate valve assessment. Each type of valve has a unique hemodynamic profile and Doppler findings, which are also affected by the valve size and the patient's body surface area.
- Doppler echocardiographic evaluation of PHVs should assess the seating of the valve, presence of a rocking motion, the functioning of the prosthetic disks or cusps, presence of any visible extrinsic masses on or around the prosthesis, evidence of valvular regurgitation, and its severity, and evidence of valvular stenosis, and its severity.
- The assessment of PHVs can be complex and challenging, and may lead to diagnostic dilemmas. Doppler-echocardiography, including two- and three-dimensional imaging, can provide a thorough examination of PHVs.

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