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TRANSESOPHAGEAL ECHOCARDIOGRAPHY

Transesophageal Echocardiographic (TEE) Evaluation of Prosthetic Valves

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GENERAL CONSIDERATIONS

The introduction of prosthetic heart valves in the 1960s dramatically altered the management and prognosis for patients with valvular heart disease. Echocardiography with Doppler is a powerful tool for the assessment of prosthetic heart valves, allowing serial noninvasive assessment of valve function and assessment for the presence and nature of prosthesis dysfunction. Although well suited for the hemodynamic assessment of prosthetic valves, transthoracic echocardiography has associated limitations for the evaluation of heart valve anatomy in general, with additional limitations in the assessment of prosthetic heart valve anatomy and function. The posterior location of heart valves and the unique echocardiographic characteristics of valve prostheses limit the anatomic detail typically afforded by transthoracic imaging. Transesophageal echocardiography (TEE) allows excellent visualization of heart valve anatomy in general, and offers significant advantages over transthoracic imaging in the assessment of prosthetic valve anatomy and function.[3] [15] [27] [28] [35] [53] [55] TEE is feasible in settings in which transthoracic imaging is not (i.e., intraoperatively), [22] [47] [48] and is not affected by limitations in ultrasound windows sometimes associated with transthoracic imaging. TEE serves as the “gold standard” for the noninvasive assessment of prosthetic valve and paraprosthetic anatomy. When used in conjunction with transthoracic imaging, TEE allows a complete anatomic and hemodynamic assessment of prosthetic heart valves.

Imaging Constraints and Artifacts

The presence of a valve prosthesis does not inherently alter the general approach to the transesophageal assessment of valve anatomy and function; however, acoustic properties associated with nonbiologic components of prosthetic heart valves affect the echocardiographic examination. Mechanical prostheses and the ring of stented bioprosthetic valves contain components made of metal, plastic, or pyrolytic carbon. These materials are strong reflectors of ultrasound energy, resulting in ultrasound attenuation and imaging artifacts. Attenuation of ultrasound energy results in insignificant ultrasound energy penetration distal to the prosthetic materials, obscuring regions distant to the valve. Reverberation artifacts are caused by multiple reflections of the ultrasound beam between the prosthetic valve and the ultrasound transducer or between two or more echo-reflective components within the prosthesis, possibly because of the large amount of ultrasound energy reflected by the prosthetic components. Reverberation artifacts associated with valve prostheses appear as a series of bright echoes originating at the location of and extending distal to the valve. A specific type of reverberation artifact results in a mirror artifact, in which reflection of the ultrasound beam between the prosthesis and the echocardiographic transducer results in second or third images of the prosthesis displayed at multiples of the distance between the prosthesis and the transducer. Side-lobe artifacts occur in conjunction with prosthetic valves, similar to their occurrence with any strong ultrasound reflector. An example of imaging artifacts associated with a mechanical mitral prosthesis is shown in Figure 1 .

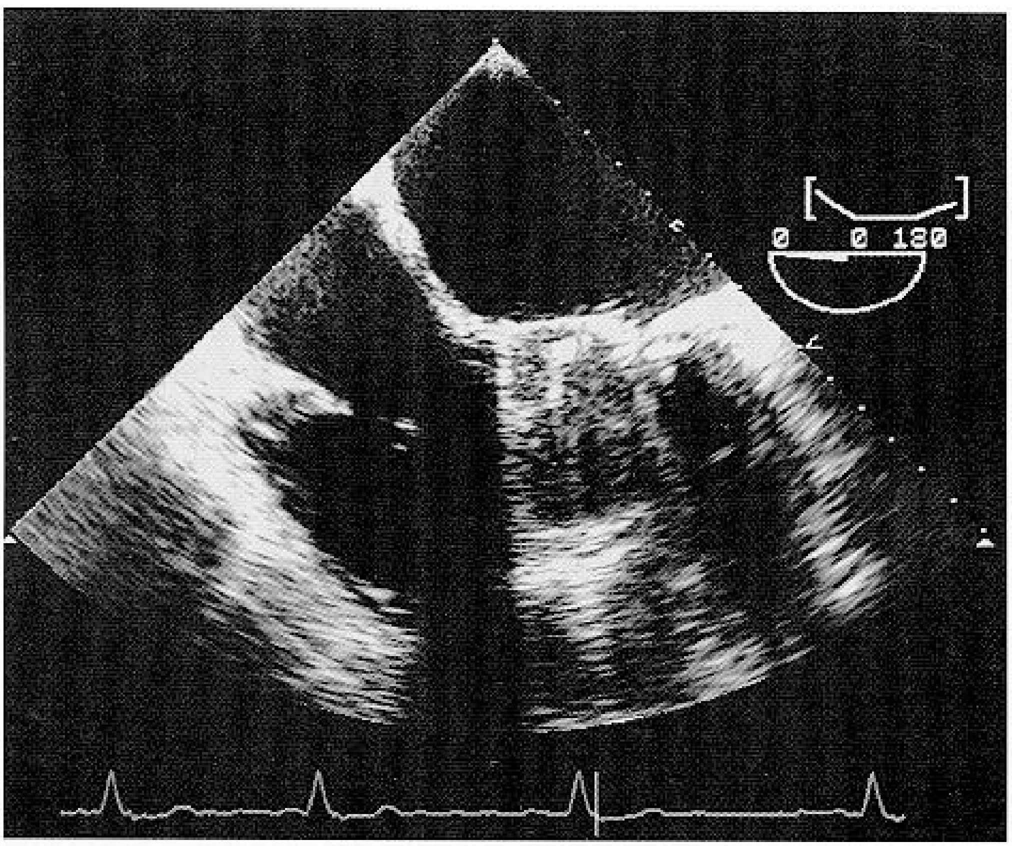


Figure 1. Ultrasound-imaging artifacts associated with mechanical prosthesis in mitral position. Reverberation artifacts appear as redundant echoes distal to prosthesis. Mirror-image artifact appears as second iteration of prosthesis displayed at twice the distance from the transducer. Acoustic shadowing results from loss of ultrasound penetration beyond prosthesis.

Signal attenuation and reverberation and side-lobe artifacts occur because of the strong echo-reflective properties of prosthetic materials used in artificial valves. An additional artifact occurs because ultrasound energy is transmitted at a different speed through prosthetic materials than through soft tissue. The ultrasound image is oriented in space and calibrated to distance based on the speed of sound. The depth of an object from the transducer is determined by the time interval required for sound energy to travel to and from the object and the known speed of sound through soft tissue. Sound energy that is propagated more rapidly through a prosthetic material than through soft tissue results in faster return of ultrasound energy to the transducer, and the object is displayed closer to the transducer than adjacent soft tissue structures. A prosthetic material in which sound energy is more slowly propagated than in soft tissue will appear more distant. Prosthetic material may appear axially displaced on the echocardiographic image, both absolutely in terms of calibrated distance and relative to adjacent tissue structures.

Because of imaging constraints associated with prosthetic materials, it may be difficult to assess the anatomy of all aspects of a valve prosthesis from a transesophageal window. Just as signal attenuation precludes assessment of posterior aspects of prostheses from an anterior, transthoracic window, the same property precludes visualization of more anterior aspects from a posterior, transesophageal window. Although **TEE** typically allows excellent assessment of prosthetic valve motion, additional anatomic information can be derived from transthoracic imaging.[54] **TEE** typically should be used as a supplement to, rather than exclusive of, transthoracic echocardiography.

Doppler Hemodynamics

As in the case with native valve lesions, limited transducer positions afforded by **TEE** may preclude accurate measurement of transvalvular prosthetic gradients. Although a Doppler signal usually can be aligned parallel to transmitral flow with a probe positioned at the midesophageal level, parallel alignment of the ultrasound beam with aortic, tricuspid, and pulmonic valve flow is more problematic. Forward flow through the aortic valve and aortic valve prostheses sometimes can be assessed from a transgastric transducer location, although orientation parallel with flow cannot be assured without assessment from multiple transducer positions afforded by transthoracic imaging from apical, right parasternal, and suprasternal windows. Transpulmonic flow can be assessed on **TEE** from a high esophageal location, although with similar limitations. Forward transtricuspid flow velocity typically is not well quantified on **TEE**, but may be possible in the longitudinal plane.

There are factors that influence the assessment of Doppler gradients through prosthetic valves and the correlation between Doppler gradients and those derived on invasive catheterization. Such factors are not inherent to **TEE** imaging. The reader is referred to discussions of general Doppler assessment of prosthetic valve gradients[1] [10] [38] [44] [50] [57] and the pressure recovery phenomenon.[7] [31]

Doppler Regurgitation

Doppler assessment of regurgitant flow typically is well assessed on **TEE** and usually better assessed than from transthoracic windows. Ultrasound attenuation impairs visualization of the left atrium from a transthoracic window in the setting of a mechanical mitral prosthesis. In contrast, the left atrium and mitral regurgitation are assessed reliably in essentially all patients on **TEE**, including patients with a mechanical mitral prosthesis.

Prosthetic aortic regurgitation (AR) usually can be assessed reliably on **TEE**, although the presence of both mitral and aortic mechanical prostheses can obscure visualization of the left ventricular outflow tract (LVOT) because of acoustic shadowing. The longitudinal plane views (90°–120°) of the LVOT may provide unimpeded visualization of prosthetic AR jets. Among patients with dual aortic and mitral mechanical prostheses, transthoracic imaging can be an important adjunct in the assessment of AR; however, forward flow through the mitral prosthesis, also diastolic, can be turbulent and directed toward the interventricular septum and confused with prosthetic AR.

Regurgitation associated with a prosthetic valve can be of valvular or paravalvular origin. Paraprosthetic regurgitation and valvular prosthetic regurgitation are caused by different mechanisms with distinct clinical implications and should be distinguished. Typically, transthoracic echocardiography is limited in its ability to determine the origin of regurgitation associated with a valve prosthesis,[13] [55] and **TEE** is often necessary. Paravalvular regurgitation is not *normal*, although small amounts (minimal or mild) of paraprosthetic mitral regurgitation are observed commonly enough on **TEE** as to be essentially an anticipated finding, especially early after valve implantation. In contrast, greater degrees of paraprosthetic regurgitation are pathological and may be of hemodynamic importance. Laboratory evidence of minor degrees of hemolysis can be detected in most patients with a mechanical prosthesis. Clinically significant hemolysis, however, can be caused by paravalvular regurgitation; the amount of hemolysis is not necessarily proportional to the severity of regurgitation.

With the exception of the caged ball valve, all other commonly used mechanical prostheses have a small amount of normal regurgitant flow through the prosthesis, intended to minimize thrombus formation. Such normal valvular regurgitation is especially apparent on **TEE** among patients with a mitral prosthesis, owing to the proximity of the transducer to the left atrium and the mitral valve. Normal valvular prosthetic regurgitation is not more than mild in severity and has a distinctive pattern unique to each type of prosthesis.[9] [26] [35] The Medtronic Hall valve (Medtronic, Minneapolis, MN), a single tilting disk prosthesis, exhibits mild central regurgitation through a hole in the occluder disk. The St. Jude Medical valve (St. Jude Medical, St. Paul, MN), a valve with two tilting semi-circular disks, exhibits a typical pattern of three small regurgitant jets: two jets are angled slightly inward at each of the two pivot points and a third central jet is seen along the line of disk coaptation. Although bioprostheses do not incorporate transvalvular regurgitation as part of valve design, minor regurgitant jets can be detected in approximately 10% of patients.

Anticipated Findings

TEE characteristics of prosthetic valves that may be normal and anticipated in some patients could be considered abnormal in other patients. As previously described, imaging artifacts are associated with many prosthetic valves, and most mechanical prostheses have a small amount of normal valvular regurgitation. **TEE** reveals thin, mobile, filamentous echoes associated with many prosthetic valves.[22] [23] [24] Although the etiology and composition of these strands have been the subject of debate, they appear to be of importance only for their recognition as a normal variant and not indicative of prosthetic valve pathology. Such fibrinous strands also can be observed among patients without a prosthetic valve, and can be distinguished from thrombus or vegetation by their filamentous structure, more closely resembling thin strands than a mass lesion.

Bright, highly mobile intracardiac echoes similar to saline contrast microbubbles also have been observed among some patients with a mechanical valve prosthesis.[25] [37] Microbubbles have been observed more often among patients with a prosthesis in the mitral than in the aortic position and more often in conjunction with disk than with caged ball valves. No adverse clinical significance has been associated with such microbubbles, and their recognition on **TEE** is important only because they should be distinguished from intracardiac mass lesions.

Indications for TEE

Although thorough anatomic assessment of many prosthetic heart valves requires combined transthoracic and transesophageal imaging, **TEE** is not necessary for the evaluation of all patients with a prosthetic valve.[9] Transthoracic imaging usually allows adequate assessment of transvalvular hemodynamics and some assessment of prosthesis anatomy. **TEE** should be considered among patients with suspected prosthesis dysfunction or question of prosthetic endocarditis. Because of the greater resolution of **TEE** in general, and because **TEE** can overcome many limitations associated with transthoracic imaging in patients with prosthetic valves, **TEE** should be considered in any patient with suspected prosthesis dysfunction. Prosthesis anatomy and function usually can be well defined, and the presence and nature of prosthesis dysfunction usually can be determined. Among patients with evidence or suspicion of prosthetic valve regurgitation, **TEE** can be instrumental in the differentiation of valvular from paravalvular origin.

TEE is instrumental in the evaluation of patients with known or suspected prosthetic valve endocarditis. **TEE** is superior to transthoracic imaging for the detection of vegetations among all patients with clinical evidence of endocarditis. Among patients with a prosthetic valve, artifacts confound the ability to detect small vegetations, and acoustic shadowing effectively precludes the transthoracic detection of vegetations in patients with a mechanical mitral prosthesis. Each of these limitations is diminished or overcome by the use of **TEE**.[15] [28] [35] [53] [55] **TEE** allows reliable visualization of paraprosthetic mitral anatomy, the left atrium, and the atrial aspect of a mitral prosthesis. Among patients with an aortic valve prosthesis, **TEE** similarly allows superior visualization of prosthetic and paraprosthetic anatomy,[3] [15] [27] including the ability to detect smaller vegetations and paravalvular abscess.

Intraoperative pre-pump **TEE** allows accurate assessment of aortic annulus size in anticipation of aortic valve allograft insertion.[36] Intraoperative post-pump **TEE** is useful to interrogate prosthesis valve function immediately after implantation and can be helpful if there is suspicion of either prosthesis dysfunction or significant paraprosthetic regurgitation. Routine use of intraoperative post-pump **TEE** is encouraged after implantation of stentless aortic bioprostheses, including allografts and stentless xenografts. With such valves, geometric distortion at the time of implantation can affect prosthesis function, and surgical revision can be performed during the same operative procedure based on post-pump **TEE**.

IMPLICATIONS OF PROSTHESIS TYPE

The specific type of valve prosthesis affects its appearance on **TEE**. The construction of a prosthesis determines its general echocardiographic appearance, influenced by mechanical versus tissue construction, disk or disks versus caged ball occluder, and stented versus stentless tissue design. Many prostheses contain highly echo-reflective materials that result in acoustic artifacts in patterns specific to the prosthesis type.

Mechanical Prostheses

All mechanical prostheses contain nonbiologic materials in the valve ring, sewing cuff, and orifice occluder and can be identified as such on **TEE**. The specific echocardiographic appearance of mechanical valves is determined by the prosthesis type and the angle of incidence of the interrogating ultrasound beam. In the case of tilting disk mechanical prostheses, strong ultrasound echo-reflectivity associated with the annular ring and the occluder create characteristic patterns of intense leading-edge echoes with associated acoustic shadowing distally, often with reverberation and mirror artifacts. If the ultrasound beam is oriented parallel with flow through the valve, disk motion occurs in an area that is not affected by acoustic shadowing from the ring and typically can be well visualized on **TEE**. Analysis of disk motion should include qualitative assessment of disk speed and excursion. Disk motion should be rapid, with movement between opened and closed positions typically occurring in time intervals below the temporal resolving power of two-dimensional echocardiographic imaging, so that the disk (or disks) appears to change position between imaging frames. The temporal resolving power of M-mode echocardiography can be used to demonstrate rapid disk motion, as shown in Figure 2 . Total disk excursion varies by specific prosthesis type and size. Tilting-disk prostheses have asymmetrical patterns of opening.[46] [58] Echocardiographic discrimination of a single-disk from a double-disk prosthesis and demonstration of total extent of disk excursion relies on careful orientation of the two-dimensional image in a plane that bisects the midline of the prosthesis perpendicular to the major disk orifice, and requires examination of the prosthesis in multiple imaging planes. The operator should be careful to interrogate methodically the prosthesis in multiple planes and, ideally, from more than one window before concluding that disk mobility is impaired, because tangential cuts through the valve can lead to underestimation of disk excursion.

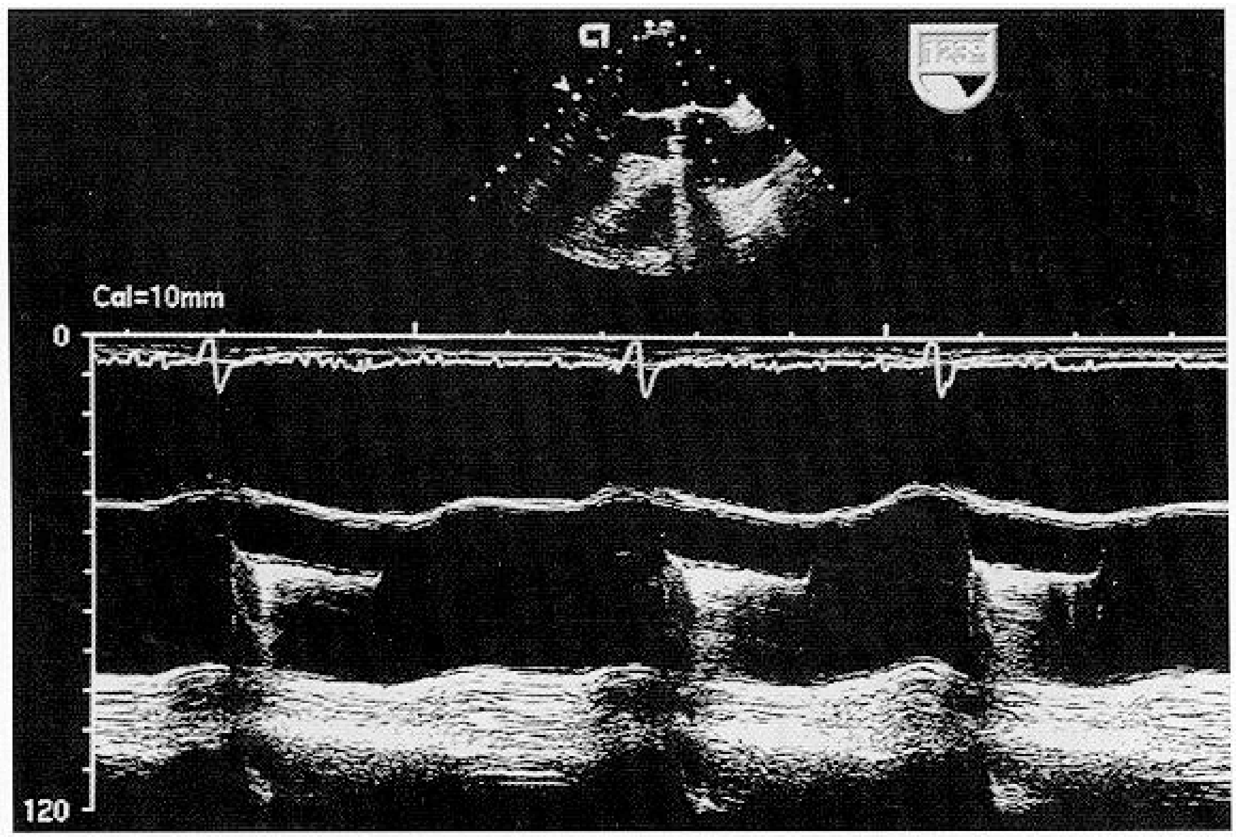


Figure 2. M-mode transesophageal echocardiogram (**TEE**) of prosthetic aortic valve disk motion. Vertical lines demonstrate rapid disk movement between open- and closed-disk positions.

Forward flow through a mechanical prosthesis can be visualized using color flow Doppler. The pattern observed in association with a normally functioning prosthesis is determined by the type of prosthesis and the plane of interrogation. When the two-dimensional echocardiographic image is aligned midline and perpendicular to the major orifice, antegrade flow can be demonstrated, sometimes in a pattern that matches the number, location, and relative size of the valve orifices. For example, dual-disk prostheses have one major and two minor orifices of flow, which can be demonstrated on **TEE**. Single tilting disk prostheses have two orifices, one major and one minor.

Similar to the tilting disk valve, the caged ball valve has associated intense leading-edge echoes associated with occluder and sewing ring. The large bulk and high profile of these valves, and the strongly echo-reflective materials from which they were manufactured, lead to extensive acoustic shadowing distal to the valve's leading edge. Ball occluder motion usually can be assessed based on the leading-edge echoes and normally demonstrates rapid motion between open and closed positions. The color flow pattern of antegrade flow through a caged ball prosthesis typically reveals substantial turbulence, creating a roughly circular pattern as blood accelerates around the periphery of the ball occluder.

Although it gained only limited clinical use, a caged disk (Cutter) valve is encountered occasionally. An example of flow through this valve is shown in Figure 3 . The valve is constructed with a caged disk occluder oriented perpendicular to flow. The circular pattern of turbulent forward flow is similar to that observed with a caged ball prosthesis, although the caged disk valve can be differentiated by its lower profile.

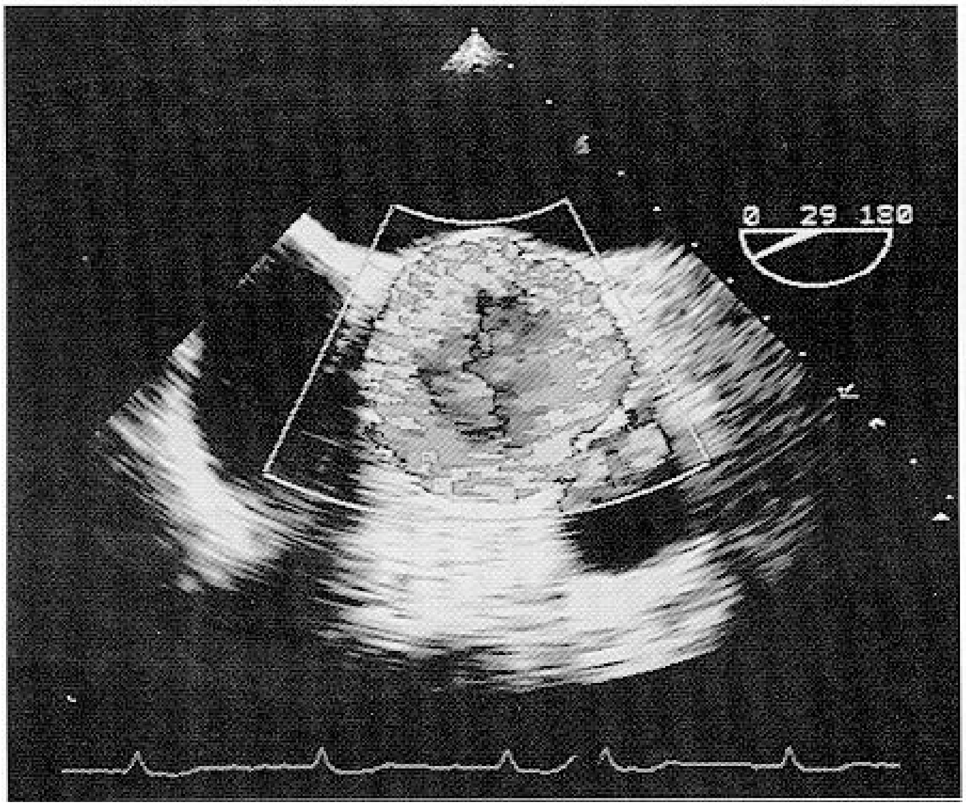


Figure 3. Turbulent antegrade flow through caged disk valve. Imaged in short axis above the prosthesis, turbulent flow enters ascending aorta around the circular disk occluder. A caged ball valve with similar flow can be distinguished by higher profile cage mechanism in long-axis view.

For all mechanical prostheses, incomplete mobility or slow movement of the prosthetic occluder should suggest prosthesis dysfunction. Transvalvular regurgitant jets associated with mechanical prostheses were discussed previously.

Stented Bioprostheses

Stented bioprostheses have associated prosthetic material in the sewing ring and struts, with associated shadowing and artifacts. In contrast, the leaflets are composed of biologic tissue, either from porcine or bovine aortic valves or from constructed bovine pericardium. The leaflets of these valves have the echocardiographic appearance of normal soft tissue, and are not associated with acoustic shadowing or side-lobe or reverberation artifacts. An example of the **TEE** appearance of a stented bioprosthesis in the tricuspid position is shown in Figure 4 . Total leaflet excursion of stented bioprosthetic valves can be less than that associated with normal, native semilunar valves, owing to the effects of the fixation process and of rigid supporting struts on leaflet flexibility. Stented bioprostheses typically have no associated transvalvular regurgitation, although a trivial central jet sometimes can be observed originating from the site of central cuspal coaptation, similar to that observed among some patients with an anatomically and functionally normal native semilunar valve. With time, bioprostheses tend to develop focal or more diffuse leaflet sclerosis visible on echocardiographic imaging. Valve failure usually occurs because of a fracture of a sclerotic or calcified cusp, typically with hemodynamically significant regurgitation.

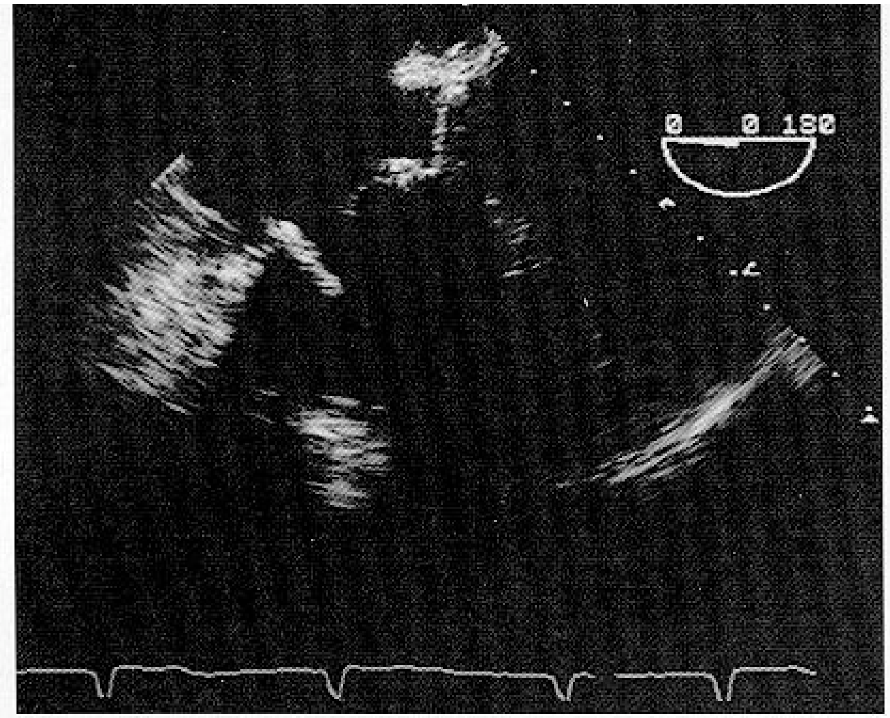


Figure 4. Bioprosthesis in tricuspid position. One of three support struts is imaged in this view. Valve leaflets are thin and of soft tissue density.

Stentless Aortic Bioprostheses

Stentless bioprostheses in the aortic position include the use of allograft, stentless xenograft valves, and the autograft (Ross) procedure, in which the native pulmonic valve is transplanted to the aortic position and replaced with a pulmonic allograft. The use of such procedures has increased in the past few years after recent approval for clinical use in the United States of two stentless xenograft valves, the Freestyle aortic root prosthesis (Medtronic, Minneapolis, MN) and the Toronto SPV valve (St. Jude Medical, St. Paul, MN). The echocardiographic appearance of a stentless aortic bioprosthesis is determined in large part by the implant technique used at the time of surgery[5] ; understanding the echocardiographic appearance of such valves requires that the echocardiographer gain some familiarity with surgical techniques used with these valves.

Allograft and Freestyle stentless xenograft implantation can be performed using a variety of surgical techniques that differ in the amount of aortic root implanted with the semilunar valve cusps, and whether the patient's aortic root is retained. Because of the absence of rigid sewing ring and struts, stentless valves require support from the ascending aortic wall. Patients with significant aortic root dilation require aortic root replacement or other intervention if there is significant dilation at the level of the sinotubular junction. This can be accomplished through the use of a stentless bioprosthesis that contains the aortic valve and aortic root, implanted using either the *full root* or *root inclusion* technique. The *root inclusion* technique involves implantation of a cylinder-shaped aortic conduit containing the aortic valve *within* the patient's ascending aorta. Using this technique, there is a double-walled ascending aorta composed of allograft or xenograft root within the patient's native aortic root. The portion of allograft or xenograft root adjacent to the patient's coronary ostia is excised. The *full root* implantation technique involves resection of the diseased aortic valve and aortic root, with interposition of the allograft or xenograft aortic root and reimplantation of the patient's coronary arteries with surrounding tissue *buttons*. In the absence of significant aortic root pathology, stentless bioprostheses can be implanted using a *complete subcoronary* or a *modified subcoronary* technique. The *complete subcoronary* technique involves implantation of the allograft or xenograft aortic valve and only as much aortic wall as is necessary to support the three semilunar cusps, resecting the three allograft or xenograft sinuses of Valsalva. The *modified subcoronary* technique involves resection of the right and left sinuses of Valsalva and retention of the noncoronary sinus. In these implantation techniques, the patient's native aortic wall supports the stentless aortic valve. Because the right and left sinuses of Valsalva are resected, coronary artery reimplantation is not necessary.

TEE allows excellent assessment of prosthetic and paraprosthetic anatomy and function following implantation of a stentless aortic bioprosthesis. Because there is no prosthetic sewing ring, prosthetic occluder, or prosthetic struts associated with stentless bioprostheses, acoustic shadowing and other imaging artifacts encountered with other prostheses are not observed. As a rule, allograft and stentless xenograft valves appear similar on echocardiographic imaging. The valve leaflets are remarkable for an echocardiographic appearance similar or sometimes indistinguishable from the normal human aortic valve. Differences in implantation technique account for differences in echocardiographic appearance of the aortic root.

As anticipated from the surgical anatomy, the echocardiographic appearance of the full root stentless bioprosthesis is remarkable for an essentially normal appearance of the ascending aorta, because there is only a single layer of aortic wall circumferentially. The echocardiographic appearance of these prostheses may closely imitate normal, and patients following full root stentless aortic valve surgery may be identifiable as other than normal only if there is evidence of focal thickening at the inlet or outlet suture lines. Patients following root inclusion stentless aortic valve implantation typically represent the opposite end of the spectrum of the echocardiographic appearance of the ascending aorta. Among these patients, there is a double layer of aortic wall circumferentially in the first few centimeters of ascending aorta, resulting in a variable degree of thickening of the aortic root evident on **TEE**. Following complete subcoronary implantation of a stentless aortic valve, minimal soft tissue thickening of the aortic wall can be evident on **TEE**. Retention of the noncoronary sinus of Valsalva with modified subcoronary implantation of a stentless aortic bioprosthesis results in a characteristic appearance on **TEE**, with soft tissue thickening of the aortic root limited to the noncoronary sinus of Valsalva and small adjacent areas of the right and left sinuses of Valsalva. Examples of the **TEE** appearance of stentless aortic bioprostheses are shown in Figures 5 and 6 .

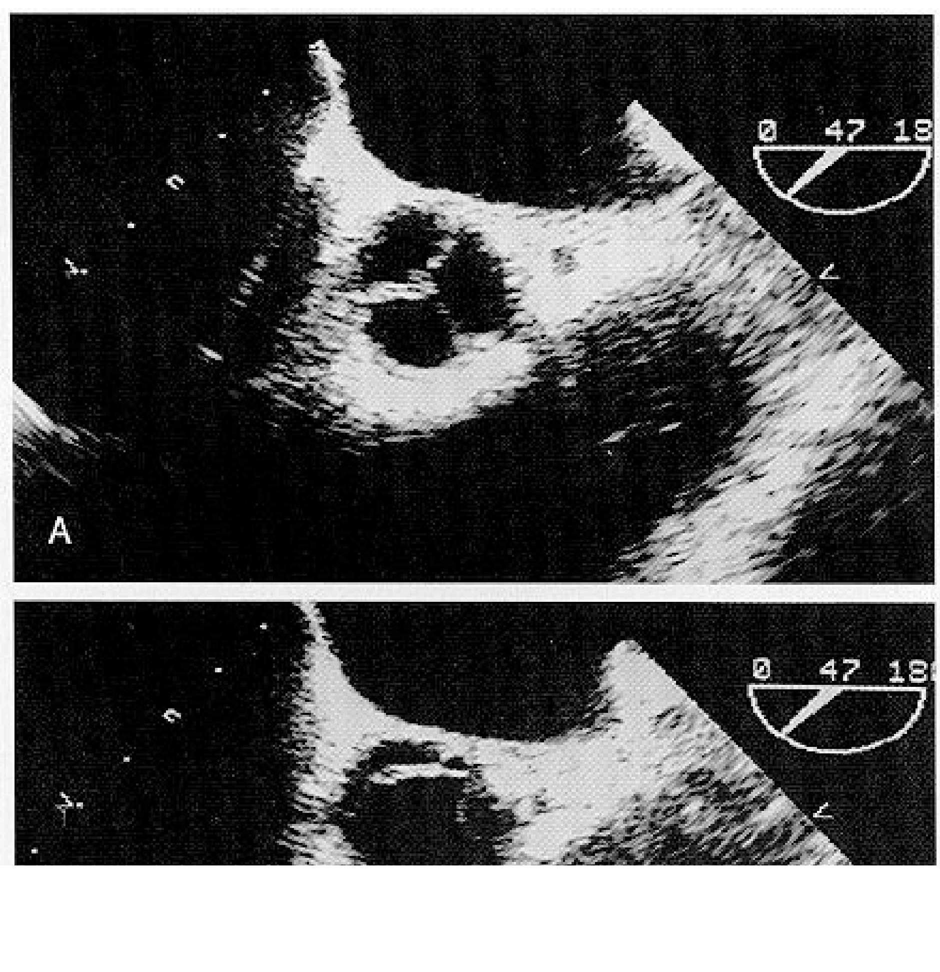


Figure 5. Short-axis view of stentless aortic bioprosthesis (subcoronary implantation) in diastole *(A)* and systole *(B)* reveals normal appearance of valve cusps and minimal paravalvular thickening.

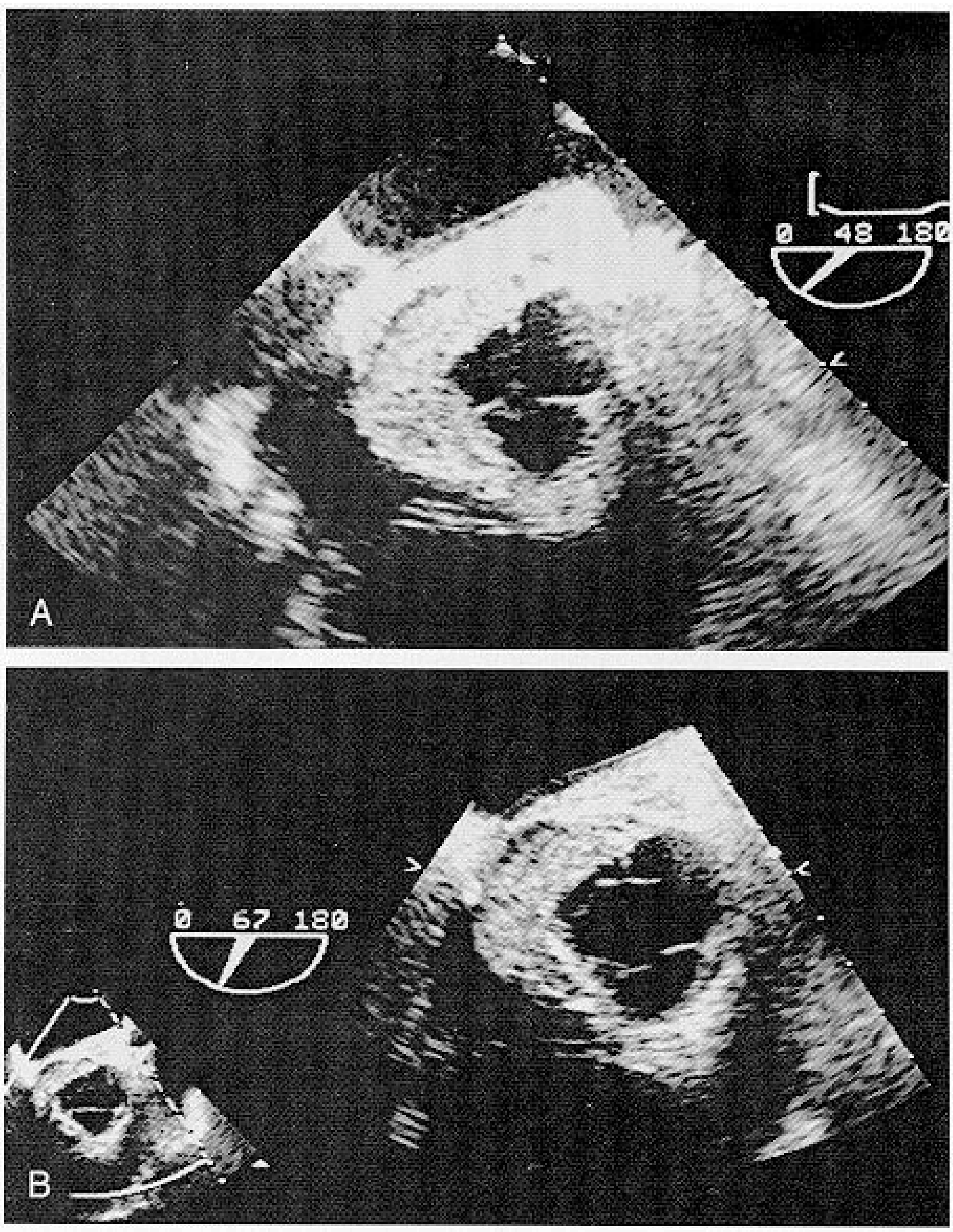


Figure 6. Short-axis view of stentless aortic bioprosthesis (modified subcoronary implantation) in diastole *(A)* and systole *(B)*. Cusps appear thin and demonstrate normal systolic mobility. Paravalvular soft tissue thickening is confined to region of noncoronary cusp, accumulating in space between native ascending aorta and retained noncoronary sinus of Valsalva.

The retention of aortic root tissue associated with the root inclusion and modified subcoronary techniques creates a potential space between the allograft or xenograft aortic wall internally and the patient's native aortic wall externally. Early after surgery, this space typically fills with blood or thrombus, which is readily evident on **TEE** performed intraoperatively or early postoperatively. Dependent on surgical and patient-related factors, the associated area of soft tissue density collection can be of variable size, and can have associated distortion or compression of the valve wall early after implantation. Although the natural history of collections of blood, thrombus, and edema has not been formally studied, anecdotal experience suggests that to a large degree these collections diminish in size within the first few weeks after surgery, and often resolve completely within a few months postoperatively. [5]

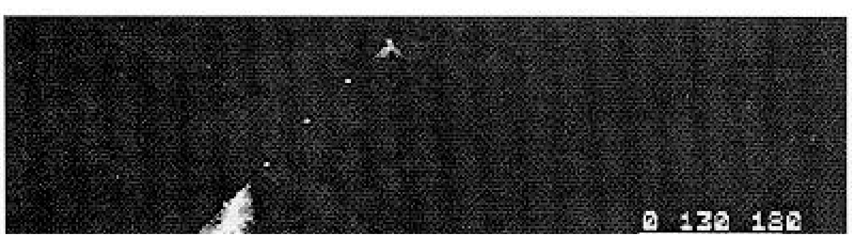
Different from stented bioprostheses and mechanical prostheses, stentless bioprostheses have two suture lines. The inflow suture line is felt to provide anatomic orientation and stability, and the outflow suture line is felt to represent the hemostatic suture line. Significant transvalvular regurgitation is uncommon after implantation of stentless aortic bioprostheses, although small amounts can be seen. Paraprosthetic regurgitation can be seen, similar to other types of prostheses. Small amounts of paravalvular regurgitation on immediate post-pump **TEE** often resolve by hospital discharge.[6]

PROSTHETIC VALVES BY LOCATION

Mitral Valve

Nearly all mitral prostheses can be well visualized and interrogated on **TEE**. At the midesophageal level, the posterior position of the ultrasound transducer relative to the prosthesis allows excellent visualization of the left atrium and the atrial aspect of the prosthesis. Normal valvular regurgitation, pathologic transvalvular regurgitation, and paraprosthetic regurgitation can be reliably detected and quantified. Because of the orientation of antegrade flow through the mitral orifice, transvalvular mitral gradients usually can be assessed on **TEE**, with good correlation with transthoracic windows.

The anatomy of a prosthetic valve in the mitral position usually can be well defined on **TEE**.[15] [28] [35] [53] [55] Acoustic shadowing does not interfere with visualization of the valve when imaging from a midesophageal window, posterior to the valve and perpendicular to the plane of the prosthetic ring. A caged ball valve can be differentiated from a tilting disk valve, and the number of disks can be determined. In order to reliably visualize both disks of a dual-disk type prosthesis, the imaging sector should be rotated through multiple planes with the transducer at the midesophageal level. Surgeons typically implant disk prostheses in an orientation intended to minimize the risk for entrapment of submitral chordae by the occluder mechanism. Single disk valves typically are positioned in an *antianatomic* orientation, with the major orifice toward the interventricular septum. Maximal disk excursion usually is best demonstrated in a long-axis view of the left ventricle, at a **TEE** imaging plane of approximately 120° from transverse. A dual-disk mitral prosthesis usually is implanted in an *anatomic* orientation that positions the pivot points at the normal locations of the anterolateral and posteromedial commissures. Simultaneous motion of both disks is again demonstrated in a long-axis orientation, at an imaging plane of approximately 120° from transverse. An example of a dual-disk mitral prosthesis on **TEE** is shown in Figure 7 . The motion of a caged ball occluder can be demonstrated similarly from a midesophageal transducer position. Although the poppet casts a large attenuation artifact, the edge closest to the ultrasound transducer is well visualized, and poppet motion can be demonstrated.



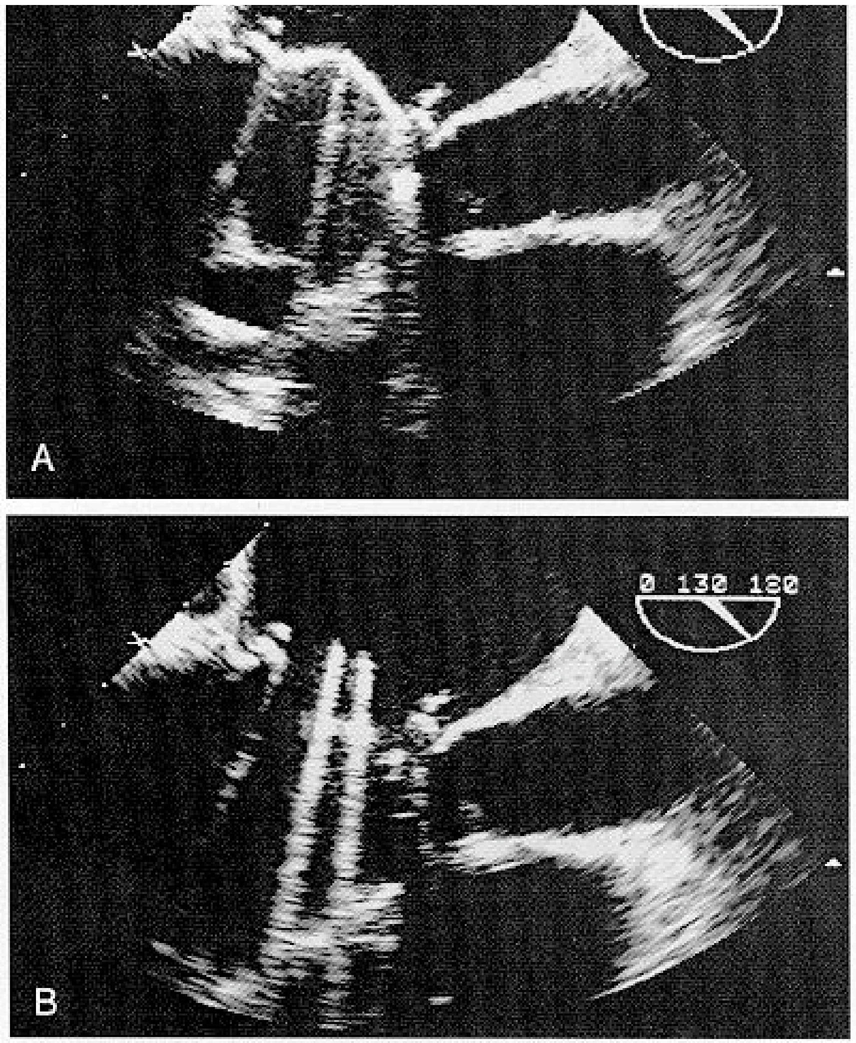


Figure 7. Long-axis view of dual disk valve (St. Jude Medical [St. Jude Medical, St. Paul, MN]) in mitral position. Valve is in typical "anatomic" orientation, with pivots placed at location of normal anterolateral and posteromedial commissures. Both disks are identified in closed position in systole *(A)* and open position in diastole *(B)*.

Although acoustic shadowing precludes anatomic assessment of the left ventricular aspect of a mechanical prosthesis in the mitral position, visualization of this aspect of the valve and of retained subvalvular mitral apparatus is usually possible using a transgastric transducer location. From this position, the prosthetic valve is distal to the submitral apparatus, and acoustic shadowing precludes visualization of the atrial but not the ventricular aspect of the prosthesis.

A tissue prosthesis in the mitral position can be well visualized similarly on **TEE**. From a midesophageal transducer position, the prosthetic valve leaflets and the atrial aspect of the sewing ring are well visualized, and valvular and paravalvular regurgitation and transvalvular gradients can be assessed reliably. Because acoustic shadowing precludes visualization of the left ventricular aspect of the prosthetic ring, **TEE** should include imaging from a transgastric transducer location.

Aortic Valve

Prostheses in the aortic position usually can be assessed adequately by **TEE**.[3] [15] [27] The aortic valve lies in a plane that is closer to perpendicular with the esophagus than does the mitral valve, however, which leads to some constraints in imaging. Because of the relative orientation of the esophagus and the plane of the aortic valve, the prosthetic ring of a mechanical or a stented tissue valve lies between the orifice of the prosthesis and a midesophageal transducer. As such, acoustic shadowing and reverberation artifact from the prosthetic ring can impede visualization of the leaflets of a stented bioprosthesis or the occluder of a mechanical prosthesis in the aortic position.

Despite these constraints, the type of prosthesis in the aortic position usually can be deduced on **TEE**. Mechanical prostheses are identified by the increased echo-reflectivity of the occluder mechanism, and the type of mechanical prosthesis can be deduced by its profile and by the number, shape, and motion of the occluder. Because of the angle of incidence of the ultrasound beam and interposition of the prosthetic ring and sewing cuff, differentiation of single-disk from dual-disk mechanical valves can be difficult, although usually possible. Without direct identification of two distinct disks, a dual-disk prosthesis can be differentiated from a single-disk prosthesis by less marked systolic excursion of the occluder into the ascending aorta. Stented and stentless tissue prostheses can be identified and differentiated by the presence or absence of prosthetic sewing cuff and struts.

In the aortic position, mechanical prostheses with asymmetrical flow profiles usually are implanted in an orientation so that flow is directed toward the greater curvature of the aortic arch. A single-disk prosthesis is oriented with the major orifice toward the noncoronary sinus of Valsalva. Imaging the ascending aorta in short axis on **TEE**, the open disk in cross-section is perpendicular to the ultrasound beam, as shown in Figure 8 . Although of less importance with respect to flow, a dual-disk prosthesis in the aortic position typically is oriented with one pivot at the junction between the left coronary and noncoronary sinuses of Valsalva, with the other placed 180° circumferentially, near the mid-point of the right coronary sinus of Valsalva. The angle of incidence of the disks imaged in short axis may differ for single- and dual-disk prostheses.

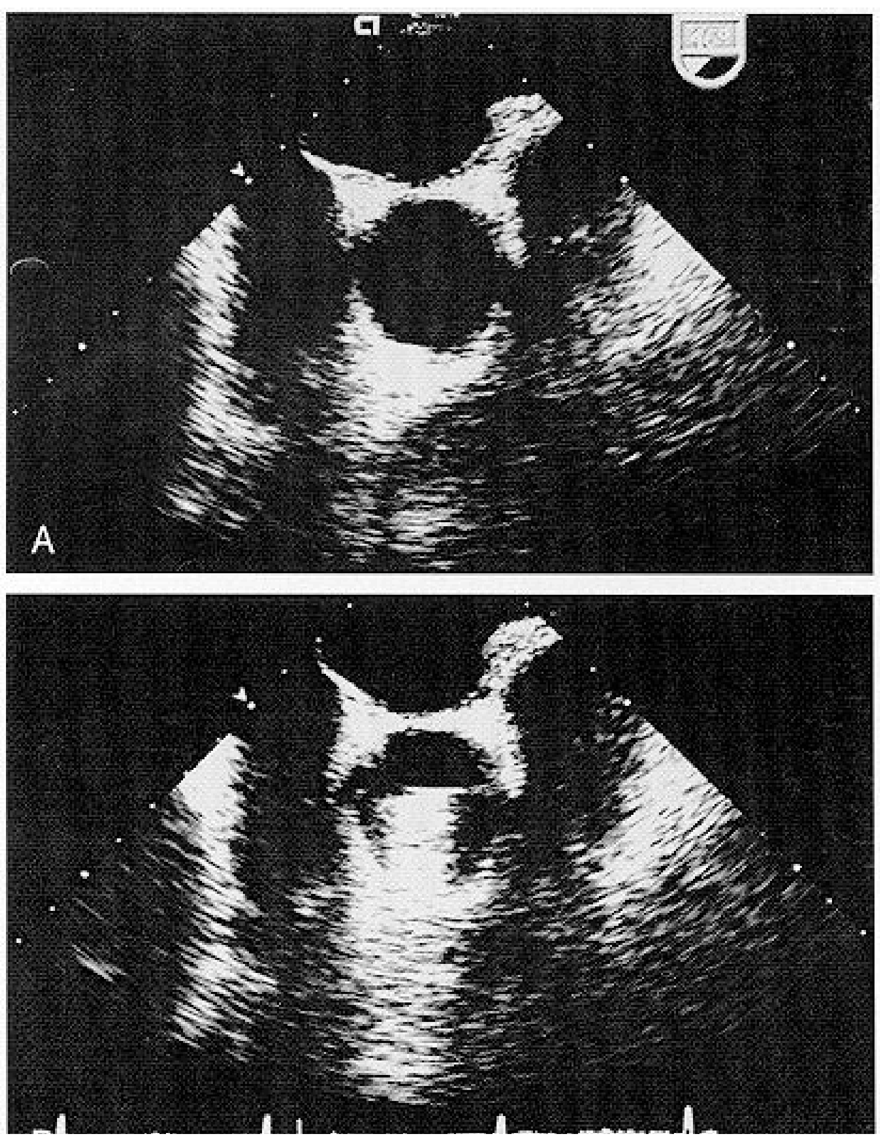


Figure 8. Short-axis view of single-disk valve (Medtronic Hall [Medtronic, Minneapolis, MN]) in aortic position. Imaging is just above level of annulus, and disk is not seen in closed position during diastole *(A)*. During systole *(B)*, open disk is oriented perpendicular to ultrasound beam.

Because the LVOT is distal to an aortic prosthesis relative to an esophageal transducer position, assessment of prosthetic aortic regurgitation is more difficult on **TEE** than is assessment of mitral regurgitation. Using both long-axis and short-axis views at a variety of transducer positions within the esophagus and stomach, it usually is possible to detect and characterize prosthetic aortic regurgitation. Many mechanical prostheses normally have associated mild valvular regurgitation,[19] [26] [35] which should be distinguished from paravalvular regurgitation or pathologic valvular regurgitation. As is the case with all prosthetic valves, **TEE** of prostheses in the aortic position early after implantation often reveals small amounts of paravalvular regurgitation, which may resolve.[6]

The plane of the aortic valve lies so that Doppler from an esophageal transducer position cannot be oriented parallel to antegrade flow, limiting the ability to quantify native or prosthetic valve gradients on **TEE**. One potential solution includes imaging from a *deep* transgastric window, so that the transducer is positioned along the lesser curve of the stomach and mimics an apical five-chamber view. Alternatively, a multiplane **TEE** probe located just beyond the gastroesophageal junction often can be rotated and manipulated so that left ventricular outflow is parallel with the Doppler signal. These views position the aortic prosthesis distal to the LVOT, and provide additional imaging windows for the **TEE** assessment of prosthetic aortic regurgitation. Assessment of transvalvular aortic gradients from these views is limited in three respects. First, these views may not be technically feasible in all patients. Second, the area of interest is placed relatively far from the ultrasound transducer, and transducer power to interrogate the region of interest may be insufficient. Third, transvalvular velocities are assessed from only one or two positions on **TEE**. Although an estimate of gradients can be made, there should be residual uncertainty with respect to the accuracy of the estimate without the ability to interrogate velocities from multiple windows. Optimal assessment of Doppler gradients across an aortic prosthesis should include transthoracic windows.

Patients with dual mechanical prostheses in the aortic and mitral position represent an especially challenging group with respect to echocardiographic imaging of the aortic prosthesis. Although the aortic prosthesis does not interfere with **TEE** assessment of the mitral prosthesis, acoustic shadowing from the mitral prosthesis compromises the midesophageal window for **TEE** assessment of the aortic prosthesis. Assessment of the aortic prosthesis on **TEE** is often limited to windows higher or lower in the esophagus than otherwise would be employed, and to windows at or distal to the gastroesophageal junction. Assessment of prosthetic aortic regurgitation may be especially problematic among patients with dual mitral and aortic mechanical prostheses. Orientation of the mitral prosthesis often directs flow toward the interventricular septum, and it can be difficult to distinguish normal, antegrade transmitral flow from pathologic prosthetic aortic regurgitation as the cause of turbulent diastolic flow in the LVOT.

Tricuspid and Pulmonic Valves

Prosthetic valves in the tricuspid and pulmonic positions are encountered much less often than in the aortic and mitral positions. The rigid circular sewing cuff of prosthetic valves distorts the crescentic shape of the tricuspid annulus, making tricuspid valve repair desirable if feasible. Low pressures inherent to the right-sided cardiac chambers typically preclude the use of a mechanical prosthesis in the tricuspid position, because insufficient pressure exists to open and close a mechanical occluder. When performed, tricuspid valve replacement usually employs the use of a bioprosthesis.

On **TEE**, the anatomy and function of a tricuspid prosthesis usually can be defined. Tricuspid regurgitation can be imaged well on **TEE** and characterized with respect to severity and origin. To decrease the risk of surgical damage to the bundle of His and iatrogenic 3° atrioventricular block, surgeons often leave a gap between sutures along the septal aspect of a tricuspid prosthesis. Mild paraprosthetic regurgitation is not uncommon following tricuspid valve replacement, with the jet emanating from the septal aspect of the annulus.

TEE can be useful in the assessment of a pulmonic valve prosthesis. A prosthesis can be identified as *mechanical, stented tissue,* or *stentless tissue,* and valvular and paraprosthetic regurgitation can be visualized and quantified. The concomitant presence of a mechanical aortic prosthesis compromises the ability to characterize pulmonic regurgitation on **TEE**. Transvalvular gradients sometimes can be assessed from a transducer position high in the esophagus, demonstrating bifurcation of the main pulmonary artery and with flow from the pulmonic valve nearly parallel with and toward the interrogating Doppler signal.

PATHOLOGY

Transthoracic echocardiography is an excellent diagnostic screening tool for patients with prosthetic valves.[9] **TEE** should be considered among patients with suspected prosthetic valve dysfunction and among those in whom transthoracic imaging does not exclude prosthesis dysfunction. The presence or absence of prosthesis dysfunction usually can be established using **TEE**, and the origin of dysfunction can be further characterized. **TEE** may be the definitive imaging modality for the diagnosis and characterization of paraprosthetic pathology.

Thrombus and Pannus Formation

Prosthetic valve thrombosis can occur with any mechanical prosthesis[20] [29] [34] [41] and has been described in association with bioprostheses.[12] The risk for thrombus formation is affected by several factors, including the location and specific type of prosthesis and the level of anticoagulation. Because of its greater orifice area and slower transvalvular flows, the same type of prosthesis used in the mitral position is at greater risk for thrombosis than when used in the aortic position. In addition, some types of mechanical prostheses are at greater risk for thrombotic complications, such as the caged ball prosthesis. Finally, the level of anticoagulation is indirectly related to risk for prosthesis thrombosis.[11]

Although transthoracic imaging can provide information to support the presence of thrombus, **TEE** usually is required to image thrombi associated with a valve prosthesis. Thrombi can be observed on the sewing cuff or less commonly attached to the occluder. Larger thrombi can partially occlude the valve orifice or interfere with occluder motion, resulting in increased transvalvular gradients. Because of imaging artifacts associated with mechanical prostheses, small thrombi that interfere with valve function are sometimes not visible, and their presence is surmised based on abnormal occluder motion.

Prosthetic valve thrombosis has been treated with intravenous thrombolytic therapy, sometimes obviating the need for surgical valve explantation. **TEE** can be a useful tool in the assessment of the adequacy and success of thrombolytic therapy for prosthetic thrombosis,[42] allowing serial assessment of thrombus size and prosthesis occluder motion.

Pannus formation consists of tissue ingrowth at the site of a prosthesis. Pannus can result in increased transvalvular gradients either because of direct compromise of the orifice or because of interference with mechanical occluder opening. Because either thrombus or pannus can interfere with prosthetic occluder motion, differentiating the two can be difficult. In either case, **TEE** demonstrates incomplete opening or incomplete closure of the valve occluder, potentially with slower than anticipated occluder motion.[20] [29] [34]

[41] Turbulent flow is observed distal to the valve, and transvalvular gradients are increased. Valvular regurgitation is evident if the occluder fails to close completely. Hemodynamically significant valvular or paravalvular regurgitation results in increased transvalvular gradients caused by the high flow crossing the fixed valve orifice. The finding of increased transvalvular gradients on transthoracic imaging can be caused by either prosthetic stenosis *or* significant prosthetic regurgitation.

Infective Endocarditis

Patients with a prosthetic heart valve are at increased risk for infective endocarditis, and prosthetic valve endocarditis is more resistant to antibiotic treatment than is native valve endocarditis. Echocardiography plays an increasingly important role in the diagnosis and management of patients with endocarditis. Because of enhanced image resolution, valvular and paravalvular anatomy that is obscured on transthoracic imaging can be assessed routinely using **TEE**. **TEE** is the imaging modality of choice in patients with a heart valve prosthesis and known or suspected infective endocarditis.

Vegetations are the characteristic lesions of infective endocarditis in association with either native or prosthetic heart valves. Vegetations in association with mechanical prosthetic valves can result in prosthesis dysfunction by impeding occluder motion, causing regurgitation, or stenosis. Rarely, a large vegetation can directly compromise the valve orifice. On echocardiographic imaging, the characteristics of a vegetation are of a soft tissue density mass of echoes with rapid oscillation and motion independent of other cardiac structures. Vegetations most commonly occur on the low pressure aspect of a turbulent jet, such as the left atrial aspect of a mitral prosthesis or the left ventricular aspect of an aortic prosthesis. Imaging constraints associated with transthoracic imaging make the detection of vegetations associated with a mechanical prosthetic valve difficult. Specifically, acoustic shadowing precludes visualization of the atrial aspect of a mechanical mitral prosthesis, and reverberation and side-lobe artifacts interfere with the detection of all but very large vegetations associated with a mechanical prosthesis in any position. An example of a vegetation associated with the left atrial aspect of a mechanical mitral valve prosthesis is shown in Figure 9 . Vegetations involving the leaflets of a bioprosthesis are visualized more reliably, owing to the absence of imaging artifacts. Endocarditis involving the leaflets of a bioprosthesis often is accompanied by some amount of tissue destruction and valvular regurgitation.

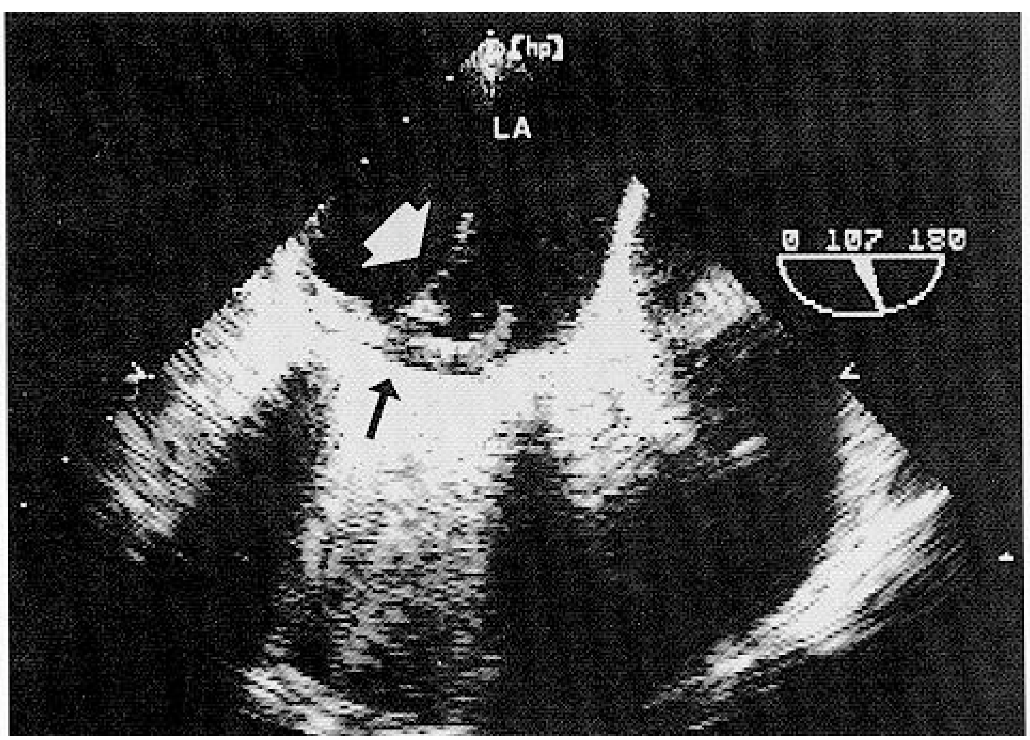


Figure 9. Vegetation *(white arrowhead)* on left atrial aspect of mechanical mitral prosthesis. Reverberation artifact *(black arrow)* obscures detail distal to prosthesis, and precludes visualization of vegetation from transthoracic windows.

TEE is associated with increased sensitivity compared with transthoracic imaging for the detection of vegetations associated with native and prosthetic valves,[8] [17] [39] [49] [52] but the incremental gain is especially significant among patients with prosthetic valves.[2] [4] [14] [28] [30] [33] [56] In one study,[14] investigators demonstrated an increase in sensitivity for the detection of mechanical prosthesis vegetations from 22% to 83%. It should be noted that imaging artifacts associated with mechanical prostheses also affect the ability to detect small vegetations using **TEE**, so that neither transthoracic echocardiography nor **TEE** can be used to definitively exclude the diagnosis of endocarditis in patients with a prosthetic heart valve. The demonstration of vegetations may establish or support a diagnosis of endocarditis, but failure to demonstrate vegetations associated with a prosthetic heart valve does not exclude it; however, normal findings on **TEE**, weighed with other clinical evidence, can decrease the likelihood of endocarditis and can exclude prosthesis dysfunction complicating endocarditis.

Patients with a prosthetic valve are at increased risk for paravalvular abscess complicating infective endocarditis. Although transthoracic imaging is relatively insensitive for the detection of paraprosthetic abscess,[16] **TEE** is relatively accurate for the detection of abscess complicating endocarditis. [15] [40] [45] [51] In the mitral position, abscess formation appears as an echo-lucent space adjacent to the prosthesis sewing cuff. In the aortic position, paravalvular abscess is suggested by abnormal thickening of the soft tissue surrounding the prosthesis, with or without a contained echo-lucent space.

Stentless aortic bioprotheses have a normal amount of surrounding soft tissue thickening evident on **TEE** early after implantation. These areas of soft tissue thickening and fluid collection between the native and allograft or xenograft aortic roots can mimic paraprosthetic abscess. It is important to recognize these as normal findings early after surgery. Probably the most reliable means to distinguish normal paraprosthetic thickening and fluid from paravalvular abscess among patients having undergone implantation of a stentless aortic bioprosthesis is to compare findings with those on immediate post-pump or early postoperative **TEE**. Progressive reduction in the extent of soft tissue thickening and the size of fluid collection makes the diagnosis of paravalvular abscess less likely. Demonstration of a progressive increase in the extent of soft tissue thickening or the size of paravalvular fluid collection should increase concern for paravalvular abscess.

Extension of the infective process adjacent to a prosthetic valve can result in fistula formation, or partial or complete valve dehiscence. Paravalvular fistulae may form between the two chambers separated by the prosthetic valve, or between chambers with no normal communication. In the former case, endocarditis is associated with significant paraprosthetic regurgitation. Because **TEE** is imperfect in the detection of small prosthetic valve vegetations, the finding of new paravalvular regurgitation should at least prompt consideration of a diagnosis of endocarditis. In patients with infection involving an aortic valve prosthesis, fistulae can form between the LVOT or ascending aorta and the right atrium, left atrium, or right ventricle. Shunts associated with such fistulous connections are readily detectable with **TEE** and should raise the concern for prosthetic valve endocarditis.

Sufficient paravalvular tissue destruction complicating prosthetic valve endocarditis can result in partial or complete valve dehiscence. On **TEE**, prosthesis dehiscence sometimes can be detected as an abnormal rocking motion of the prosthesis independent of its surrounding structures. An example of dehiscence of an aortic valve prosthesis is shown in Figure 10 . Prosthetic valve dehiscence is accompanied by significant paravalvular regurgitation. The finding on **TEE** of a broad-based paravalvular regurgitant jet emanating from a significant portion of the circumference of the prosthesis suggests partial valve dehiscence; the extent of the valve's circumference from which the jet emanates is a marker for the extent of dehiscence. An example of a broad-based paravalvular regurgitant jet associated with prosthetic aortic valve endocarditis is shown in

Figure 11 .

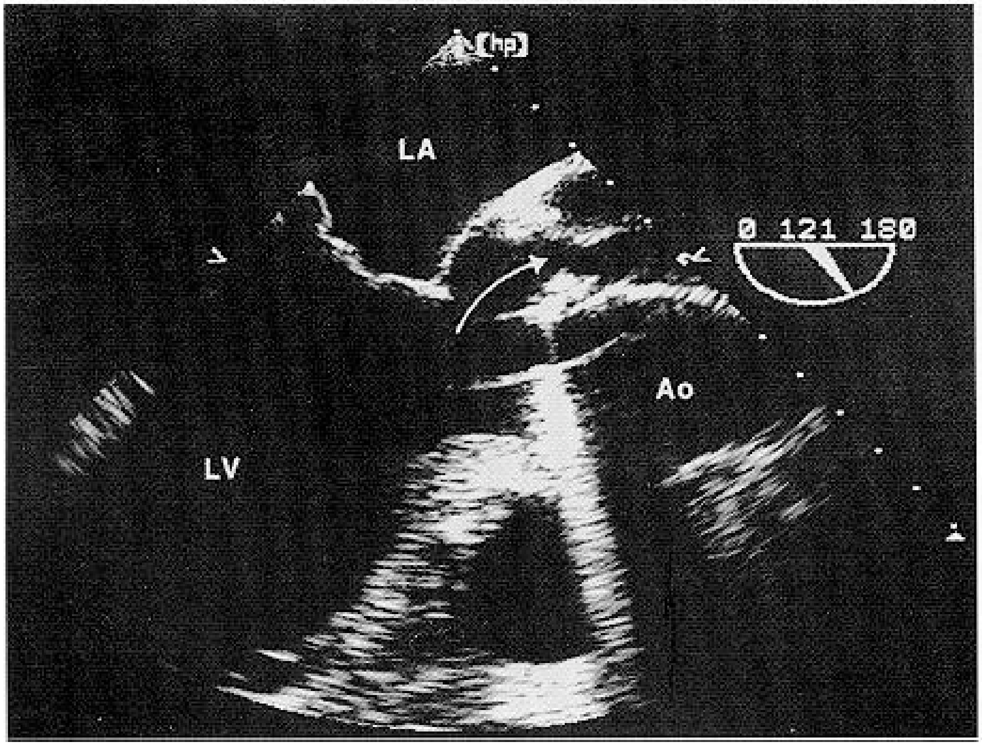


Figure 10. Long-axis view of left ventricular outflow tract (LVOT) and ascending aorta, demonstrating dehiscence *(arrow)* of valved aortic root composite graft complicating infective endocarditis.

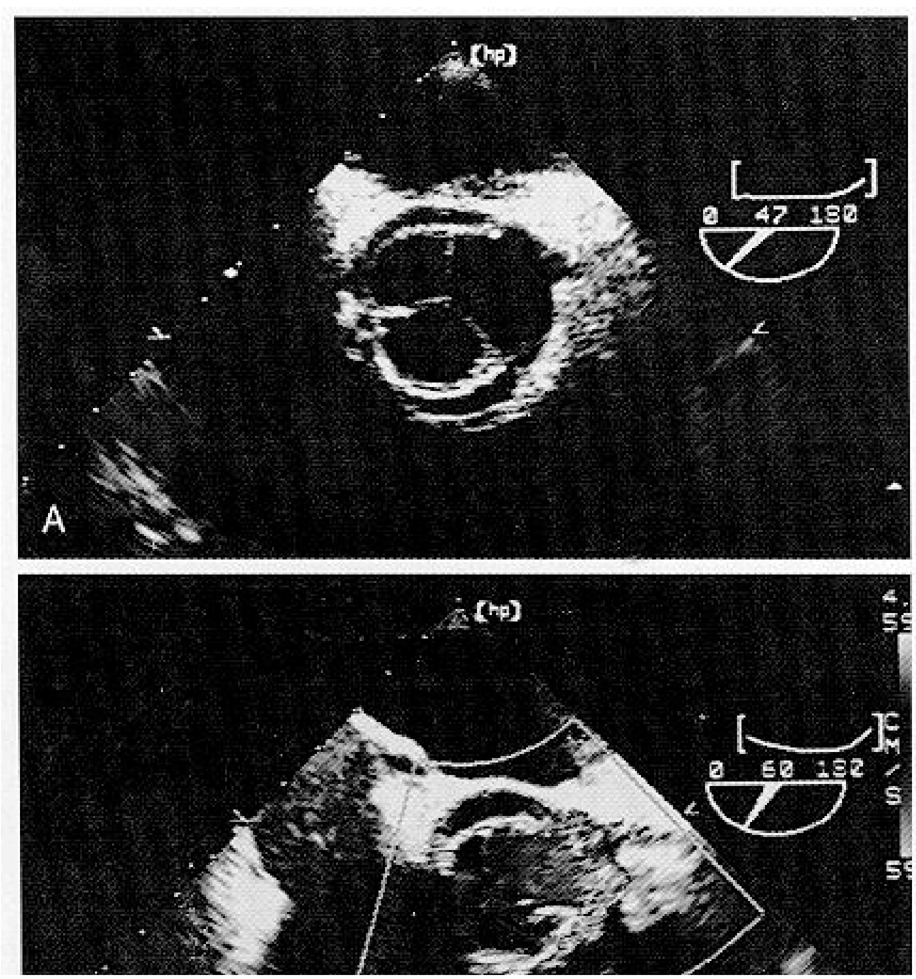


Figure 11. Short-axis view of stentless aortic bioprosthesis with partial dehiscence *(A)* and broad-based paravalvular aortic regurgitation jet *(B)*.

In addition to helping establish a diagnosis of endocarditis and assess for paravalvular complications of infection, **TEE** can be used to help assess adequacy of antimicrobial therapy. Serial **TEE** imaging allows assessment of change in vegetation or abscess size[30] [51] and can help establish the success or failure of nonsurgical therapy.

Mechanical Failure

All prosthetic heart valves are subject to mechanical failure, mediated by the mechanical stresses associated with repeated opening and closing inherent to valve function. The time course and nature of mechanical failure are influenced by factors related to the prosthesis type and location, and factors specific to the patient.

In general, bioprostheses are prone to mechanical failure earlier than mechanical prostheses, and a bioprosthesis in the mitral position is prone to failure before a similar prosthesis in the aortic position.[21] Identifiable patient-specific factors that predispose to earlier mechanical failure of a bioprosthesis include young age (because of increased calcium metabolism) and concomitant renal dysfunction or other conditions associated with abnormal calcium homeostasis and predilection to dystrophic calcification.

Bioprosthesis deterioration is caused by fracture of the nonviable collagen fibers at points of flexion,[18] with subsequent sclerosis and tissue calcification. With advancing prosthesis age, **TEE** reveals progressive changes in the appearance of the tissue leaflets. Originally thin leaflets develop evidence of focal and then more diffuse thickening and sclerosis. Although transvalvular gradients may increase as sclerosis worsens, bioprosthesis failure usually is caused by leaflet fracture with regurgitation, which is often acute. **TEE** reveals significant valvular regurgitation and may reveal flail motion of the fractured cusp.[59] The regurgitant jet may be eccentric but is usually broad based, with deep penetration. High frequency vibration of the fractured cusp can cause a characteristic *zebra stripe* appearance on spectral Doppler imaging through the regurgitant jet.

Most mechanical valves are remarkably durable and not prone to mechanical failure, although some exceptions exist. Most notable is the Björk-Shiley convexo-concave disk type prosthesis, which is subject to strut fracture and subsequent disk embolization. No echocardiographic factors are predictive of strut fatigue or impending strut fracture. **TEE** findings after failure of a mechanical prosthesis reveal severe regurgitation, and may reveal the absence of an occluder if failure involved its destruction or embolization.

Paraprosthetic Regurgitation

Infective endocarditis can be associated with paravalvular regurgitation; however, paraprosthetic regurgitation also can occur in the absence of an infective process. Paravalvular regurgitation occurs either at the time of surgery, if there is an incomplete seal formed between the sewing cuff and the annulus, or later, if there is suture failure. Small amounts of paravalvular regurgitation early after surgery are common. Because of its proximity to the left atrium, minimal or mild paravalvular mitral regurgitation often can be identified on **TEE** early following implantation of a mitral valve prosthesis. Small paravalvular regurgitant jets may decrease over time, with the process of organization and healing at the site of valve insertion. Heavy mitral annular calcification is a risk factor for paravalvular regurgitation. Paravalvular regurgitation that first occurs in the days or weeks after surgery may represent failed sutures that have pulled free from their annular insertion. Later development of significant paraprosthetic regurgitation often is caused by an infective process and may herald paravalvular involvement of prosthetic valve endocarditis. An example of paravalvular regurgitation associated with a mechanical mitral prosthesis is shown in Figure 12 . Valvular dehiscence was discussed with endocarditis previously.

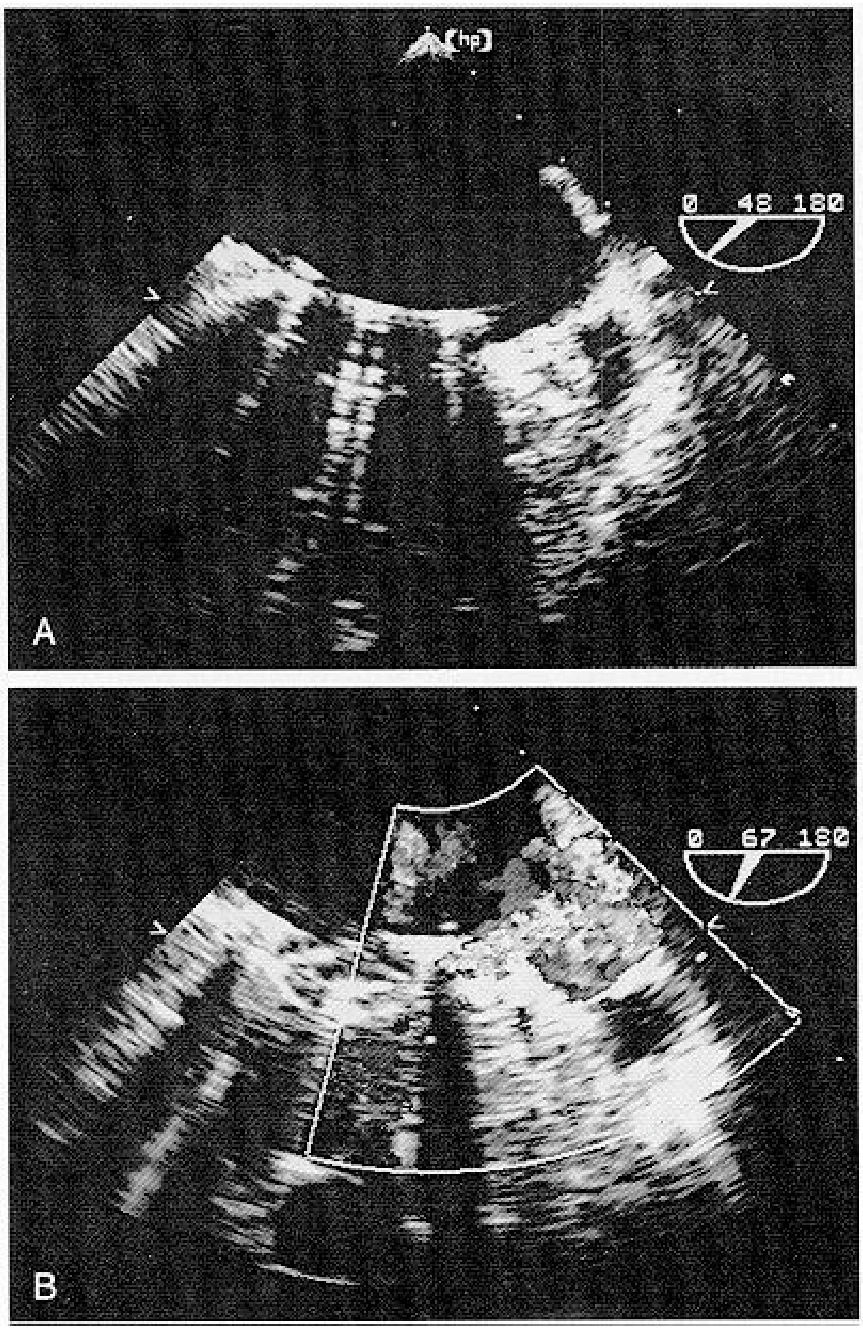


Figure 12. Dual-disk mechanical mitral prosthesis open during diastole *(A)*, with paravalvular mitral regurgitation *(B)*. Paraprosthetic regurgitation impacts left atrium near left atrial appendage.

Prosthesis Patient Mismatch

Prosthesis patient mismatch implies inadequate hemodynamic performance of a prosthetic valve in a specific patient despite normal function of the device.[43] The commonest scenario in which prosthesis patient mismatch is encountered is among small patients (especially women) after aortic valve replacement for aortic stenosis. Nearly all prosthetic valves have some amount of inherent functional stenosis because of the presence of a sewing cuff within the annulus, which limits the effective orifice area of the prosthesis relative to its external annular diameter. Compromise of effective orifice area by mechanical components is more problematic in the aortic annulus than the mitral, and especially when the annulus is small. Some prostheses have a greater potential for prosthesis patient mismatch; stented bioprostheses in the aortic position tend to have higher transvalvular gradients and greater potential for prosthesis patient mismatch than do mechanical prostheses or stentless bioprostheses.

The importance of echocardiography and **TEE** among patients with suspected prosthesis patient mismatch is to exclude other pathology that can result in increased transvalvular gradients, such as pannus or thrombus formation or, in the case of mechanical prostheses, incomplete occluder opening. The hallmark of prosthesis patient mismatch on **TEE** is the finding of normal prosthetic valve function despite high transvalvular gradients.

SUMMARY

TEE overcomes many of the imaging constraints associated with transthoracic echocardiography for the assessment of valvular anatomy and function. Additional imaging artifacts and constraints associated with prosthetic valves are minimized or overcome with **TEE**. As such, **TEE** allows assessment of prosthetic valve anatomy and function and paraprosthetic anatomy, and serves as the diagnostic imaging modality of choice for patients with suspected prosthesis dysfunction or endocarditis.

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