Noninvasive Evaluation of Normal and Abnormal Prosthetic Valve Function

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Noninvasive techniques are helpful in evaluating the function of mechanical prostheses and tissue valves. Combined phonocardiography and M-mode echocardiography together with cinefluoroscopy are the most useful noninvasive techniques in differentiating normal from abnormal metallic prosthetic valve function. The intensity of the opening and closing clicks and associated murmurs will depend on the type of prosthetic valve, the heart rate and rhythm and the underlying hemodynamic status. Arrhythmias or conduction disturbances, or both, may produce motion patterns that mimic some of the echocardiographic signs of malfunctioning prosthetic valves. Differentiation of thrombus formation or tissue ingrowth from paravalvular regurgitation or dehiscence is possible by noninvasive techniques. Disc variance, a potentially serious and lethal problem with the older Beall valves, can be readily detected by cinefluoroscopy and echophonocardiography.

With regard to bioprosthetic valves, two-dimensional echocardiography is superior to M-mode echocardiography in detecting primary valve failure. In addition, detection of vegetations, valve alignment and ring and individual leaflet motion can be best accomplished by two-dimensional echocardiography. Of greater importance is the patient serving as his or her own control in the follow-up assessment of prosthetic valve function by noninvasive techniques.

Since the first successful valve replacements by Harken et al. (1) and Starr and Edwards (2) in 1960 with mechanical prosthesis, the natural history of symptomatic valvular heart disease has been altered. Despite the improvement in the design and manufacture of prosthetic valves, malfunction still occurs. With greater clinical experience and the use of newer noninvasive techniques, earlier detection of prosthetic valve malfunction is possible. The ideal prosthetic valve should be nonobstructive, nonthrombogenic and durable and its function should be readily evaluated by noninvasive techniques.

Evaluation of a patient with suspected prosthetic heart valve malfunction should begin with a careful history and physical examination. Before suspecting malfunction, it is important that the clinician be aware of the normal auscultatory findings in patients with prosthetic valves. Depending on the type and location of a prosthesis, varying auscultatory findings may be encountered. The intensity of the opening and closing clicks, their character or associated murmurs, or both, will depend on the type of prosthetic valve, the heart rate and rhythm and the underlying hemodynamic status (3).

Noninvasive Techniques in Evaluation of Prosthetic Valve Function

Combined M-mode echocardiography and phonocardiography. Despite the normal auscultatory findings for each particular prosthetic valve, there are inherent difficulties in evaluating patients with suspected prosthetic valve malfunction. A murmur may be absent in severe prosthetic paravalvular regurgitation. In addition, multiple clicks may be present and cause confusion as to the exact origin of the click in patients with more than one prosthetic valve. For these reasons, we recommend combined echophonocardiography in patients with prosthetic valves so that the origin of sounds, murmurs and timing of intervals can be accurately assessed.

The main advantage of combined echophonocardiography is that auscultatory events in relation to valve motion can be recorded in graphic form with essentially no time delay. Several phonocardiographic time intervals have been measured (Table I). These include electrocardiographic Q wave-mitral valve closure interval, Q-aortic valve opening interval and S1-aortic valve opening interval; however, none of these intervals has much practical value (4). Measurement

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and, therefore, cinefluoroscopy may not always be helpful. The tissue bioprostheses have limited radiopacity in cases, the technique is particularly useful in evaluating patients with a metallic valve, including central ball and disc occluders. The tissue bioprostheses have limited radiopacity and, therefore, cinefluoroscopy may not always be helpful.

**Table 1. Phonocardiographic Time Intervals**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Normal Range (second)</th>
<th>Clinical Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2-MVO</td>
<td>0.06 to 0.12</td>
<td>Shortened A2-MVO indicates mitral obstruction or severe mitral regurgitation and rarely left ventricular dysfunction. Prolonged A2-MVO may indicate sticking valve as with tissue ingrowth or left ventricular dysfunction</td>
</tr>
<tr>
<td>A2-TVO</td>
<td>0.08 to 0.13</td>
<td>Same as for mitral valve</td>
</tr>
<tr>
<td>Q-MI*</td>
<td>0.055 to 0.09</td>
<td>Markedly prolonged interval indicates high left atrial pressure and obstruction</td>
</tr>
<tr>
<td>S1-AVO*</td>
<td>0.07 to 0.09</td>
<td>Markedly prolonged interval indicates tissue ingrowth</td>
</tr>
<tr>
<td>Ratio of AO/AC (Starr–Edwards valve only)</td>
<td>&gt; 0.50</td>
<td>Less than 0.50 indicates variance</td>
</tr>
</tbody>
</table>

*Usually of minimal value.

AC = aortic closure click; AO = aortic opening click; AVO = aortic valve opening; A2 = aortic component of the second heart sound; MVO = mitral valve opening; M1 = mitral component of the first heart sound; Q = Q wave on electrocardiogram; S1 = first heart sound; TVO = tricuspid valve opening.

of the A2-mitral valve opening interval in patients with suspected mitral valve prosthesis malfunction is an extremely important and useful measurement (5). An abnormally short A2-mitral valve opening interval indicates high left atrial pressure from either valve obstruction, paravalvular regurgitation or left ventricular dysfunction. Although an abnormally prolonged A2-mitral valve opening interval has been reported in patients with prosthetic obstruction due to severe tissue ingrowth or thrombus formation, severe left ventricular dysfunction may be responsible. With regard to the tilting disc prosthesis, such as the Björk-Shiley valve and the St. Jude bileaflet prosthesis, the A2-mitral valve opening interval can only be measured by the use of combined echophonocardiography because the opening sound is not audible. In patients with a tricuspid prosthesis, the interval between the aortic valve closure and tricuspid valve opening is generally similar to the A2-mitral valve opening.

The use of the patient as his or her own control is essential in following up patients with suspected valve malfunction (6). Subtle changes may not be appreciated if there is no baseline study for comparison. Long rhythm strips are necessary so that multiple cycles can be recorded, especially in patients with arrhythmias.

**Cinefluoroscopy.** Cinefluoroscopy is valuable in diagnosing suspected prosthetic valve dysfunction (7). In most cases, the technique is particularly useful in evaluating patients with a metallic valve, including central ball and disc occluders. The tissue bioprosthesis have limited radiopacity and, therefore, cinefluoroscopy may not always be helpful.

**Two-dimensional echocardiography.** The value of two-dimensional echocardiography in detecting mechanical prosthetic valve malfunction is limited because of side lobe echoes emanating from the suture ring and reverberating echoes from the ball or disc (8). There are limited reports of two-dimensional echocardiography in detecting prosthetic valve malfunction (9–11). In one study (11) the technique correctly diagnosed malfunction in only 6 (26%) of 23 patients who had either valve dehiscence or a large pedunculated vegetation.

**Doppler ultrasound.** Continuous wave Doppler recording utilizing a dual transducer system, one transducer for transmitting sound energy and one for receiving back-scattered waves, has been used to evaluate prosthetic valve function (12). The pulsed Doppler technique, which is based on one transducer acting as both transmitter and receiver as well as allowing a selection of a period of time during the returning cycle and permitting the interrogation of a specific structure (13), may be useful in quantifying the degree of paravalvular leak. Although the estimation of the degree of mitral regurgitation has been reported by range-gated pulsed Doppler echocardiography (14), it is more difficult to assess mitral prosthetic regurgitation than aortic prosthetic regurgitation (12).

**Spectral analysis.** Recently, spectral analysis has been used to evaluate normal and abnormal closure sounds in patients with an aortic porcine xenograft (15). Thus, the detection of early degeneration of an aortic porcine bioprosthesis may be accomplished by spectral analysis before other clinical manifestations are apparent. The Fourier transform method of spectral analysis may be less accurate than the maximal entropy method. In the former system, the frequency resolution is directly proportional to the duration of the signal; because aortic porcine valve closing sounds are only 15 to 25 ms in duration, the technique may be limited. The maximal entropy method is not limited in resolution and, therefore, may be more accurate for analysis of signals of short duration, such as aortic heterograft closure sounds (16).

**Normal Prosthetic Valve Function: Auscultatory, Echophonocardiographic and Cinefluoroscopic Findings**

A basic knowledge of the individual prosthetic valves with regard to their advantages and disadvantages is helpful in understanding prosthetic valve malfunction. The commonly used prosthetic valves are listed in Table 2. For purposes of this report, the five underlined basic prototype prosthetic valves will be discussed under the following headings: auscultatory findings, echophonocardiographic findings and cinefluoroscopic findings. Table 3 summarizes the echophonocardiographic findings of the five prototype normal prosthetic valves.
**Table 2. Commonly Used Prosthetic Valves**

<table>
<thead>
<tr>
<th>Type of Valve</th>
<th>Position</th>
<th>OC</th>
<th>CC</th>
<th>SM</th>
<th>DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central ball occluder</td>
<td>Aortic</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Starr-Edwards</td>
<td>Mitral</td>
<td>+</td>
<td>+</td>
<td>±</td>
<td>-</td>
</tr>
<tr>
<td>Smeloff-Cutter</td>
<td>Tricuspid</td>
<td>+</td>
<td>+</td>
<td>±</td>
<td>-</td>
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<tr>
<td>Braunwald-Cutter</td>
<td></td>
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<td>Magovern-Cromie</td>
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<tr>
<td>Harken</td>
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<tr>
<td>DeBakey-Surgitool</td>
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<tr>
<td>Hufnagel</td>
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<td></td>
</tr>
<tr>
<td>Central disc occluder</td>
<td>Mitral</td>
<td>+</td>
<td>+</td>
<td>±</td>
<td>-</td>
</tr>
<tr>
<td>Beall-Surgitool</td>
<td>Tricuspid</td>
<td>+</td>
<td>+</td>
<td>±</td>
<td>-</td>
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<tr>
<td>Cooley-Cutter</td>
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<tr>
<td>Kay-Shiley</td>
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<td>Kay-Suzuki</td>
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<td>Cross-Jones</td>
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<tr>
<td>Eccentric monocuspid disc</td>
<td>Mitral</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Bjork-Shiley</td>
<td>Tricuspid</td>
<td>±</td>
<td>+</td>
<td>-</td>
<td>±</td>
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<tr>
<td>Lillehei-Kaster</td>
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<tr>
<td>Hall-Kaster</td>
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<tr>
<td>Wada-Cutter</td>
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<tr>
<td>Bileaflet prosthesis</td>
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<td>±</td>
<td>+</td>
<td>-</td>
<td>±</td>
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<tr>
<td>St. Jude</td>
<td>Tricuspid</td>
<td>±</td>
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<td>-</td>
<td>±</td>
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<tr>
<td>Tissue valves or bioprosthesis</td>
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**Table 3. Echophonocardiographic Findings of Normal Prosthetic Valves**

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<tr>
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<tr>
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<td>-</td>
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<td>Smeloff-Cutter</td>
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<td>+</td>
<td>±</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Central disc occluder</td>
<td>Mitral</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beall-Surgitool</td>
<td>Tricuspid</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>±</td>
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<td>Cooley-Cutter</td>
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<td>Eccentric monocuspid disc</td>
<td>Mitral</td>
<td>±</td>
<td>+</td>
<td>-</td>
<td>+</td>
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<tr>
<td>Bjork-Shiley</td>
<td>Tricuspid</td>
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<tr>
<td>Bileaflet prosthesis: St Jude</td>
<td>Mitral</td>
<td>±</td>
<td>+</td>
<td>-</td>
<td>±</td>
</tr>
<tr>
<td>Tricuspid</td>
<td>±</td>
<td>+</td>
<td>-</td>
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<tr>
<td>Bioprosthesis (or tissue valve)</td>
<td>Aortic</td>
<td>±</td>
<td>+</td>
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<tr>
<td>Pulmonary</td>
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<tr>
<td>Hancock</td>
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<tr>
<td>Tricuspid</td>
<td>±</td>
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**Central Ball Occluder: Starr-Edwards Valves**

**Auscultatory and phonocardiographic findings.** The Starr-Edwards valves have easily audible opening and closing sounds that coincide with maximal excursion of the ball and subsequent seating. In the aortic position, a loud opening click is produced usually 0.06 to 0.07 second after the first component of the first heart sound (Fig. 1). The normal amplitude ratio of the aortic opening to closing sound by phonocardiography is usually greater than 0.5. A reduction in this ratio suggests prosthetic valve malfunction (17). Low cardiac output and premature ventricular contractions may result in a decreased intensity of the aortic prosthetic clicks. In addition, a grade 2/6 early crescendo-decrescendo systolic murmur that radiates into the carotid vessels may be present. The murmur can be caused by turbulence or a transvalvular gradient, or both. The pressure difference reflects the fact that with the caged ball, blood flow through the valve is peripheral, around the circumference of the ball, and is therefore turbulent. The murmur may be quite loud and harsh and may increase in intensity when stroke volume is augmented, such as during anemia, anxiety or tachycardia (3). Multiple systolic clicks have been recorded in association with a bouncing poppet (18). An early diastolic mur-
mur is generally regarded as pathologic and indicative of paravalvular leak or abnormal seating of the ball.

In the mitral position, both the opening and closing clicks are well recorded. The prominent opening click usually follows the aortic component of the second sound within 0.06 to 0.13 second (Fig. 1) (19). This interval increases slightly after an increase in the preceding RR interval. An apical early to mid-systolic murmur may be commonly heard at the left lower sternal border, and is probably produced by turbulence as a result of the projection of the rigid prosthesis cage into the left ventricular outflow tract. An apical diastolic murmur is distinctly abnormal and should suggest prosthetic dysfunction or obstruction.

Echocardiography. The original Silastic anterior and
posterior surfaces of the ball can readily be recorded by echocardiography (Fig. 1). The velocity of sound through Silastic is different from that through soft tissue. With relative slowness of sound transmission through Silastic, an apparent increase in the ball diameter as measured by ultrasound technique is found (20).

With the model 6400 hollow titanium metal ball, only the anterior surface of the ball can be recorded by echocardiography. On occasion, however, the posterior echo of the ball may be obtained when the valve is examined off axis. The opening and closing motion of the valve can be recorded. In the mitral position, the valve remains open throughout diastole with a slope that resembles that of mitral stenosis. The original emphasis had been placed on measuring ball excursion and opening and closing velocities. However, in our experience this has not been shown to be a valuable method of studying patients with suspected prosthetic valve malfunction. A variety of factors, including the position of the patient and the effect of gravity, can also affect the opening velocity of motion of the mitral valve.

**Cinefluoroscopy.** The features of the aortic 2400 valve on X-ray examination include a single groove encircling the base ring. The metal studs may be difficult to delineate in poor quality films. The double cage structure may or may not be apparent and the cages are joined at the apex. The radiopaque poppet seats close to its equator in diastole. In most cases, the mitral valve has a normal tilting angle of 12° during systole. The greater range of tilting motion in the mitral prosthesis is related to the more dynamic motion of the mitral anulus compared with the aortic root.

**Central Occluder Valves: Beall Surgitool**

**Auscultation.** Central disc occluder valves are generally inserted in the mitral and tricuspid positions only. The Beall valve will produce an opening and closing sound similar to that from a ball valve. In the mitral position, the opening sound is generally loud and the A2-mitral valve opening interval measures from 0.07 to 0.11 second (6). This interval is not affected by atrial fibrillation or long RR intervals. A systolic murmur is not produced because the valve is a low profile valve and generally does not produce outflow obstruction. Diastolic murmurs may occasionally be heard if smaller valves are inserted or if tissue ingrowth or thrombus formation occurs. The resulting turbulent blood flow across the open valve may be responsible for the audible diastolic murmur.

**Echocardiography and cinefluoroscopy.** Disc excursions with opening and closing sounds is readily recorded in the mitral position (Fig. 3). In addition, the anterior stent is also recorded. Normal opening and closure motion of the disc can be readily evaluated by cinefluoroscopy with regard to the Beall 104 and 106 prostheses (Fig. 2). The degree of tilting for a Beall mitral valve is similar to that of a Starr-Edwards valve. Slight cocking or actual sticking of the disc may be appreciated by cinefluoroscopy.

**Eccentric Monocuspid Valve: Björk-Shiley Valves**

**Auscultation and phonocardiography.** In the aortic position, the opening of the disc valve is not heard but may be recorded by phonocardiography as a soft sound occurring 0.04 second after the first sound (3). A loud distinct closure with a clicking quality is audible (Fig. 4), and is generally louder than the first heart sound. Decreased intensity of the
aortic closure sound may indicate abnormal seating of the disc in association with a thrombus or low cardiac output (23). A soft early to midsystolic ejection murmur is commonly heard in patients with an aortic Björk-Shiley prosthesis, but this may be more intense in patients with a valve of small diameter. A soft diastolic murmur is also frequently noted. This is a common clinical finding and a mild degree of aortic regurgitation can be documented at the time of cardiac catheterization (24).

In the mitral position, the Björk-Shiley valve generally does not produce an opening sound. However, phonocardiography may record a soft prosthetic opening sound at the apex or left sternal border at the onset of disc motion despite the fact that it is not heard (3). The A2-mitral valve opening interval is generally shorter, measuring 0.05 to 0.09 second (Fig. 4). A loud mitral valve closure sound is audible at the apex unless first degree atrioventricular block or left ventricular dysfunction is present. Some investigators (25) have reported a grade 2/6, early to mid-systolic ejection murmur with an eccentric monocuspid valve as well as a diastolic murmur. It has been suggested that turbulent blood flow across the valve may be responsible for the diastolic murmur.

**Echocardiography.** The motion of the disc can be recorded by M-mode echocardiography (26). Two-dimensional echocardiography is usually of minimal value because multiple reverberating echoes arising from the suture ring and metallic disc are recorded in the left atrium.

In the aortic position, multiple echoes are usually recorded behind the left atrium as a result of the reverberating echoes emanating from the disc. However, the closure movement is often recorded in association with a loud closure sound (Fig. 4).

In the mitral position, the characteristic echocardiographic pattern consists of a normal tilting disc with a brisk
Figure 4. **Center left.** A Björk-Shiley aortic valve in the open position; **Upper left.** Schematic diagram of phonocardiogram (PCG); **Upper right.** Combined phonoechocardiogram. In the aortic position, the disc opens to about 60° from the horizontal plane of the valve, with a minor orifice to the left and a major orifice to the right. A crescendo-decrescendo systolic murmur (SM) is generally recorded as a result of turbulence of flow, and a loud closure sound (CC) is produced as the valve seats itself. Usually no opening click is recorded in the aortic position. Multiple echoes emanate from the disc and reverberate behind the aortic root into the left atrium (LA). **Center left.** A Björk-Shiley mitral valve in the open position; **Lower left.** Schematic diagram of low frequency (LF) phonocardiogram; **Lower right.** Combined echophonoocardiogram. In the mitral position, the valve opens to approximately 50° from the horizontal plane of the valve and an opening sound is not produced. Therefore, the A2-mitral valve opening interval has to be measured by the simultaneous echophonoocardiogram. In this example, the A2-mitral valve opening (MVO) interval measures 0.07 second. With the onset of diastole, there is a brisk opening movement, a sharp E point and then a prolonged EF slope. With the onset of systole, the valve closes abruptly and produces a loud closure sound (CC). A diastolic murmur (DM) may be recorded as a result of valve mismatch or obstruction due to tissue ingrowth or clot.
opening motion, sharp E point and a prolonged EF slope. The valve then closes abruptly with the onset of ventricular systole and a closure sound is recorded (Fig. 4). Because the mitral valve opening sound cannot be heard, combined echophonocardiographic studies should be done to record the A2-mitral valve opening interval.

Cinefluoroscopy. The normal tilting angle of the aortic Björk-Shiley valve between systole and diastole is 10° and that of the Björk-Shiley mitral valve 9° (27). An opening angle less than 60° in a Björk-Shiley aortic valve disc prosthesis or a closing angle of the disc greater than 0° is indicative of prosthetic valve malfunction. The maximal opening of the tilting disc valve is related to the mean systolic ejection rate, cardiac output and maximal instantaneous aortic flow (28). Less than full opening can occur with an abnormally low mean systolic ejection rate and low levels of cardiac output and aortic flow. With regard to the mitral Björk-Shiley valve, an opening angle less than 50° and a closing angle of the disc greater than 0° is indicative of prosthesis malfunction (27). The newer Björk-Shiley valves, in which a thin radiopaque wire encircles the disc, can only be evaluated by cinefluoroscopy (Fig. 5).

Bileaflet Prosthesis: St Jude Valve

Auscultation. The auscultatory findings of the St. Jude cardiac valve prosthesis are similar to those of the eccentric monocuspid valve (29). In the aortic position, no aortic opening sound is audible, although occasionally a soft click can be recorded. A prominent, high pitched, metallic closing sound is audible and coincides with valve closure (Fig. 6) (30). A short, mid-systolic, crescendo-decrescendo, grade 2/6 systolic murmur is often audible at the right second intercostal space, radiating into the neck and representing turbulence of flow across the valve. An aortic diastolic murmur in the aortic position is distinctly abnormal and prosthetic paravalvular leak should be suspected. A mid-diastolic rumble has been recorded in patients with a normally functioning St. Jude mitral valve prosthesis (29); it probably represents turbulence of flow through three separate orifices in diastole.

Echocardiography. In patients with the St. Jude aortic valve prosthesis, leaflet motion is generally recorded by M-mode echocardiography (29,31,32). The echoes appear within the left atrium and the pattern is indistinguishable from that obtained in patients with an aortic eccentric monocuspid valve. However, in some patients, distinct leaflet motion can be recorded within the aortic root (Fig. 6). Rapid aortic valve closure coincides with a loud closure sound.

In the mitral position, an echo-free space separating the two leaflets is recorded during diastole (Fig. 6). On occasion, however, asynchronous early diastolic closure of the posterior leaflet has been observed in patients with atrial fibrillation and long cycle lengths (32). Gravitational effects will produce early posterior leaflet closure when the plane of the leaflet fulcra is perpendicular to gravity (32). A mitral valve opening sound may be recorded but is not audible; therefore, the A2-mitral valve opening interval must be determined by combined echophonocardiography.

Two-dimensional echocardiography can provide direct visualization of valvular motion, especially if the leaflets are perpendicular to the echocardiographic plane of the long axis of the ventricle (33).

Cinefluoroscopy. Although each leaflet is impregnated with tungsten, 5 to 10% by weight, before it is coated with pyrolitic carbon, cinefluoroscopy cannot detect individual leaflet motion in the majority of cases unless specific techniques are employed (34). Great variability in the position of the prosthetic valve in the heart makes alignment of both leaflets tangential to the X-ray beam difficult. Motion of the mitral valve is more difficult to demonstrate by cinefluoroscopy than is aortic valve motion. However, on occasion both leaflets can be seen in the same orientation during systole and diastole in both the aortic and mitral valve positions.

Bioprosthesis: Hancock Valve

Auscultation. Auscultatory sounds of tissue valves are indistinguishable from those of normal valves (3). In the aortic position, the aortic closure sound is well heard in the second right and left intercostal space although an aortic
Figure 6. **Center left.** A St. Jude aortic valve in the open position; **Upper left.** Schematic diagram of phonocardiogram; **Right.** Combined echophonocardiogram. In the aortic position, a soft crescendo-decrescendo systolic murmur (SM) is recorded. Generally, an opening click is not recorded and a loud closure click (CC) is recorded coinciding with closure movement of the valve. When the valve is fully closed, the leaflets abut against the suture ring. When they open, the anterior leaflet (AL) moves posteriorly and the posterior leaflet (PL) moves anteriorly with some separation between the two leaflets.

**Center left,** A St. Jude mitral valve in the open position; **Lower left.** Schematic diagram of phonocardiogram; **Lower right.** Combined echophonocardiogram. In the mitral position, an opening click is not produced and a diastolic murmur (DM) may be audible as a result of flow through three orifices or valve tissue mismatch. Because the opening click is not always recordable, the A2-mitral valve opening (MVO) interval has to be measured with simultaneous echophonocardiography. The valve moves from a closed position during systole to an open position with the anterior leaflet (AL) moving posteriorly and the posterior leaflet (PL) moving anteriorly (small arrow) separated by a space. A closure sound (CC) is generally recorded as the valve closes in systole. ECG = electrocardiogram; HF = high frequency; LF = low frequency; P2 = pulmonary component of the second heart sound; S1 = first heart sound; S2 = second heart sound; SR = suture ring; ULSB = upper left sternal border.
Figure 7. **Center left.** Aortic porcine Hancock valve; **Upper and lower left.** schematic diagrams of phonocardiogram; **Right.** M-mode echocardiogram of the porcine Hancock valve in aortic position (top) and mitral position (bottom). **In the aortic position,** the leaflets open in a box-like structure during systole. The anterior and posterior stents (A.S. and P.S.) are clearly recorded. With aortic valve closure, a loud aortic closure (A.C.) sound is produced that is indistinguishable from a normally occurring aortic sound. A systolic murmur (S.M.) is generally recorded that represents turbulence of flow due to the rest pressure gradient or results from the stents protruding into the aorta. **In the mitral position,** a mitral opening snap (M.O.) occurs coinciding with maximal motion of the leaflets during diastole. The leaflets remain in an open position throughout diastole and come together during systole. Systolic and diastolic (D.M.) murmurs can be recorded as discussed in the text. AML = anterior mitral leaflet; M.C. = mitral closure; PML = posterior mitral leaflet; other abbreviations as before.
opening sound is not audible (Fig. 7). A high frequency, grade 2/6 early to mid-systolic murmur is located at the left sternal border. A diastolic murmur is not heard and, if present, should be considered abnormal in the aortic position.

In the mitral position, an opening sound may be detected by auscultation in approximately half of the patients. The sound generally occurs 0.07 to 0.11 second after the second heart sound and is best heard at the apex (3). An apical diastolic murmur has been recorded in one-half to two-thirds of patients (35,36). The diastolic murmur may be related to turbulence of flow or to a valve gradient caused by a small orifice, protruding stents or a flexible resonating stent. In one-half to two-thirds of the patients, an apical and left sternal mid-systolic murmur has been recorded (37). These murmurs may increase with the administration of amyl nitrate, suggesting that the murmurs are related to turbulence resulting from the projecting stents into the outflow tract of the left ventricle. The mitral closing sound may be indistinguishable from the normal first component of the first heart sound.

Echocardiography. Horowitz et al. (38) described the in vitro and in vivo echocardiographic characteristics of the stent-mounted, gluteraldehyde-preserved, porcine aortic bioprosthesis. The M-mode echocardiogram in patients with a porcine heterograft valve demonstrates two strong and distinct parallel bands of echoes from the far and near portions of the circular stent (Fig. 7). The outer surface of the anterior band of echoes to the outer surface of the posterior band corresponds to the actual diameter of the stent. Within these bands of echoes, individual motion of the aortic leaflets can be recorded. The stent moves anteriorly during systole and posteriorly during diastole (Fig. 7).

In the aortic position, the leaflet opening motion occurs during systole, with merging of the leaflets during diastole. Similar-appearing valve motion is seen in patients with a porcine bioprosthetic valve in the pulmonary position (Fig. 8). A right ventricular-pulmonary artery conduit with a porcine bioprosthetic valve is inserted in patients with a variety of complex congenital heart disorders. The excursion of the heterograft aortic leaflets is similar to the aortic leaflets but generally less than mitral valve leaflets. In the mitral position, the opening motion of the leaflets occurs during diastole, with merging together at the onset of systole.

Individual leaflet motion and valve alignment may be better recognized with two-dimensional than with M-mode echocardiography (Fig. 9) (39). With two-dimensional echocardiography, investigators have been able to differentiate valvular problems from left ventricular dysfunction (40,41).

Cinefluoroscopy. Excessive mobility of the disc prosthesis can be detected by cinefluoroscopy. There are differences in the radiopaque base ring between the Hancock and Carpentier-Edwards valves. The Hancock valve has a radiopaque circle at its base, whereas the individual stents of the Carpentier-Edwards valve are radiopaque.

Figure 8. M-mode echocardiogram of a porcine Hancock valve in the pulmonary position. During systole, the posterior leaflet demonstrates coarse vibratory motion as depicted by the wide arrow. The leaflets merge together during diastole in the midline. The coarse vibratory motion may be explained by abnormal flow patterns as a result of residual pulmonary hypertension in this patient.

Effect of Cardiac Arrhythmias on Prosthetic Valve Motion

The characteristic echocardiographic motion of normally functioning prosthetic valves can be influenced by various rhythm and conduction disturbances. These altered motion patterns may mimic some of the echocardiographic signs of malfunctioning prosthetic valves and, thus, are clinically important. Furthermore, the changes occurring during cardiac arrhythmias can elucidate some of the physiologic mechanisms of prosthetic valve motion and closure. Because aortic prosthetic valve motion cannot always be assessed clearly by echocardiography, most of the changes produced by arrhythmias are observed in mitral prosthetic valves (Table 4).

Normal Sinus Rhythm: Effect of the PR Interval

Hemodynamics. During sinus rhythm with a normal PR interval, the hemodynamics of prosthetic mitral valve motion are similar to those of the normal mitral valve influenced mainly by the left ventricular-left atrial pressure gradient and mitral valve flow (42,43). The prosthetic mitral valve opens passively at the onset of diastole and maintains an open position throughout diastole as a result of a persistent
Figure 9. M-mode (A) and two-dimensional (B) echocardiogram from a patient with a Hancock porcine mitral valve. A, The M-mode echocardiogram depicts the individual leaflets opening during diastole (thin arrows) and merging together during systole. The anterior stent (AS) and posterior stent (PS) are visualized (wide arrows). B, Two-dimensional echocardiogram (upper panel) and schematic diagram (lower panel) of Hancock porcine mitral valve. In the left panel, the leaflets open during diastole with the two leaflets opposed to the individual stents (white arrowheads). In the right panel, the leaflets come together in the midline during systole and can be clearly seen. The individual stents (white arrowheads) and alignment of the prosthetic valve are visualized. A = anterior; AC = anterior cusp; AO = aorta; IVS = interventricular septum; LA = left atrium; LAPW = left atrial posterior wall; LPW = left ventricular posterior wall; P = posterior; PC = posterior cusp; RV = right ventricle.

atrioventricular (AV) pressure gradient. Atrial systole results in an increase in the left ventricular pressure and reversal of the AV gradient, thus initiating the closure of the prosthetic mitral valve (43–45). Valve closure is completed 63 to 87 ms after the onset of QRS complex by the pressure

Table 4. Effect of Abnormal Heart Rhythm and Conduction on the Normal Echocardiographic Pattern of Prosthetic Mitral Valves

<table>
<thead>
<tr>
<th>Abnormal Heart Rhythm</th>
<th>Conduction Effect on Echocardiography</th>
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<tbody>
<tr>
<td>Normal sinus rhythm</td>
<td>Late diastolic &quot;bump&quot;</td>
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<tr>
<td>First degree AV block</td>
<td>Premature diastolic closure</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td></td>
</tr>
<tr>
<td>a) Premature diastolic closure</td>
<td></td>
</tr>
<tr>
<td>b) Intermittent closure and opening corresponding to coarse fibrillation waves</td>
<td></td>
</tr>
<tr>
<td>c) Increased separation between ball and anterior cage</td>
<td></td>
</tr>
<tr>
<td>Atrial flutter, atrial tachycardia</td>
<td></td>
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<tr>
<td>Diastolic closure induced by flutter or P waves</td>
<td></td>
</tr>
<tr>
<td>Complete heart block</td>
<td></td>
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<tr>
<td>Diastolic closure and reopening induced by the atrial contraction (corresponding with the P waves)</td>
<td></td>
</tr>
<tr>
<td>Pacemakers</td>
<td></td>
</tr>
<tr>
<td>a) Ventricular pacing: diastolic closure and reopening in the presence of underlying complete heart block</td>
<td></td>
</tr>
<tr>
<td>b) Atrial or AV sequential pacing: premature diastolic closure in the presence of prolonged AV interval</td>
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</table>

AV = atrioventricular.
developed from left ventricular contraction (43,46,47). When prolonged AV conduction is present, the earlier atrial contraction induces a ventriculoatrial pressure gradient, and premature partial or complete valve closure occurs before end-diastole (48,49).

**Echocardiographic findings.** A late diastolic “bump” on the nontissue prosthetic mitral valve echocardiogram can be observed, corresponding to the P wave on the electrocardiogram and representing the effect of the atrial contraction (Fig. 10A). This late diastolic bump should be distinguished from an early diastolic bump on a Björk-Shiley valve, which may indicate a paravalvular leak (50) or clot formation (51), and from an early diastolic notch on a Beall valve (52) or a Starr-Edwards valve, suggesting variance of the prosthetic valve.

Premature closure of the prosthetic mitral valve has been demonstrated in the presence of first degree AV block (Fig. 10B) (42,53,54). It is clinically important to recognize that this premature closure in end-diastole can also be observed in patients with a prosthetic mitral valve and acute severe aortic regurgitation (55,56).

**Complete Heart Block**

Echocardiographic studies (47,57) of patients with complete heart block and a normal mitral valve demonstrated early closure and reopening of the mitral valve in diastole induced by the atrial contraction. The same findings are observed in patients with a disc prosthetic valve and complete heart block. Atrial systole coincident with P waves induces a mid-diastolic closure of the prosthetic valve which may reopen in late diastole depending on the interval between the P wave and the onset of the QRS complex. Similar phenomena can be seen in patients with ventricular pacing and underlying complete heart block (Fig. 11).

**Atrial Arrhythmias**

**Atrial fibrillation.** An inverse relation between the length of the preceding R-R cycle and the onset of QRS-closure interval of the prosthetic mitral valve has been found in atrial fibrillation (42,58). Thus, patients with long R-R cycles (slow ventricular response of atrial fibrillation) may demonstrate premature diastolic closure of the prosthetic mitral valve (Fig. 12). The mechanism of this early closure is unknown, but may be related to the development of a critical left ventricular volume or pressure during the prolonged filling period, resulting in closure of the valve before the ventricular contraction (59). The recent study of Busch et al. (60) emphasized the influence of gravity on the premature closure of prosthetic mitral valves. When patients were examined in the supine or right decubitus position, premature closure occurred. Premature closure was never observed in the upright or prone position, even during extremely long diastolic periods of atrial fibrillation. In addition, partial diastolic closure and reopening of the Beall mitral valve corresponding to the coarse fibrillation waves may be observed in some patients (Fig. 12).

**Atrial flutter and tachycardia.** Early diastolic closure of the Starr-Edwards ball valve and Björk-Shiley disc valve has also been described during atrial flutter with greater than 2:1 AV block and during atrial tachycardia (61). Flutter waves can generate an effective atrial contraction (62), which can close the prosthetic mitral valve in diastole by reversing the AV pressure gradient (61).

These changes in the echocardiographic motion pattern of a prosthetic mitral valve during atrial arrhythmias and complete heart block (Table 4) should be distinguished from the abnormal intermittent or incomplete opening and closing of a malfunctioning prosthetic valve, usually caused by clot formation (63,64).
Figure 11. M-mode echocardiogram showing motion of a St. Jude prosthetic mitral valve in a patient with a ventricular pacemaker and atrioventricular dissociation. Mid-diastolic closure of both leaflets (wide arrow) is seen with a PR interval of 400 ms. The valve reopens slightly in late diastole just before ventricular contraction. With a PR interval of 300 ms, premature late diastolic closure of the valve is noted (wide arrow). When the PR interval is normal (150 ms), no premature closure of the valve is seen. ECG = electrocardiogram.

Figure 12. Simultaneous electrocardiogram (ECG), phonocardiogram (PHONO) and M-mode echocardiogram from a patient with a normally functioning Beall disc valve during atrial fibrillation. When there is a long cycle length, the valve closes prematurely in diastole. In addition, coarse fibrillatory waves produce reopening and closure motion (white arrows). Note that, the reopening motion is not complete. With the onset of the delayed QRS complex, the intensity of the closure click (CC) is thus reduced. OC = opening click; SR = suture ring.
Noninvasive Evaluation of Prosthetic Valve Malfunction

The causes of prosthetic valve malfunction are presented in Table 5. In addition to the listed valve problems, hemorrhagic complications of anticoagulation therapy may occur in patients with mechanical valves.

Thrombus Formation (Table 6)

**Starr-Edwards valve.** Poppet immobilization and thrombosed mitral Starr-Edwards poppet have been recognized by the absence of demonstrable independent anterior and posterior poppet motion, despite the presence of normal cage and suture ring echoes (65). In addition, thrombus or tissue ingrowth may prevent full excursion of the ball or poppet, especially if reduced intensity of the opening and closing clicks are recorded. Patients with poppet sticking exhibit marked prolongation of the A₂-mitral valve interval beyond 0.17 second. A thrombus within the valve is identified by the apparent lack of contact of the anterior ball and cage echoes and by full excursion of the poppet. In the aortic position, the inability to demonstrate multiple clicks in association with the buncing motion of the poppet may suggest a thrombosed aortic poppet (18). With cinefluoroscopy, restriction of motion of the poppet has been reported (7). In addition, lack of complete seating of the ball within the valve orifice suggests the presence of thrombus formation, tissue ingrowth or a combination of both.

**Beall valve.** Delayed opening has been reported in patients with a thrombosed Beall valve (66,67). In one such patient, initial opening occurred 0.07 second after the second sound, but was delayed till 0.24 second until full opening occurred (6). The delayed rapid opening may be explained by the development of high left atrial pressure due to thrombus or tissue ingrowth on struts to the point of opening the valve late in diastole. On occasion, the valve may only open after atrial contraction (68). However, delayed opening can also occur in the absence of a malfunctioning valve and may be due to left ventricular dysfunction.

**Björk-Shiley valve.** The Björk-Shiley prosthesis is more susceptible to thrombus formation in the mitral than in the aortic position. The rounding of the E point may indicate thrombus or obstruction (50). If there has been a significant reduction in excursion in association with marked rounding of the initial motion of the Björk-Shiley mitral prosthesis (as compared with the baseline postoperative study), thrombosis of the valve should be strongly suspected (Fig. 13). The thrombosed Björk-Shiley prosthesis can be recognized echocardiographically by reduced or zero amplitude of valve excursion in association with dense echoes in the region of the suture ring (69). This finding is especially significant in the absence of a demonstrable closing click. Patients with extensive clot formation in and around the Björk-Shiley aortic valve may have complete absence of disc motion associated with dense echoes in the aortic root (23). Cinefluoroscopy is helpful and shows impaired excursion of the prosthetic disc (7).

**St. Jude valve.** In patients with a clotted St. Jude mitral cardiac prosthesis, the A₂-mitral valve opening interval may be markedly shortened (29). In addition, abnormal rounding of the opening motion as compared with a baseline study has been reported (Fig. 14) (29). This occurred in association with a markedly decreased closing click. We have had no experience in detecting thrombosed St. Jude aortic leaflets.

Paravalvular Regurgitation (Table 7)

In patients who have paravalvular regurgitation, mitral or aortic regurgitation murmurs are usually heard. However, in some instances, despite the occurrence of significant paravalvular regurgitation, no murmurs may be audible (Fig. 15). Significant hemolysis is usually present in these patients. Patients can present with severe anemia or progressive congestive heart failure, or both.

**Mitral valve.** Patients with paravalvular mitral regurgitation have a shortened A₂-mitral valve opening interval, irrespective of the type of valve prosthesis. However, a shortened A₂-mitral valve opening interval can occur in patients with left ventricular dysfunction. An early diastolic bump of the Björk-Shiley mitral prosthetic valve has also been reported in patients with paravalvular leaks (Fig. 15) (50). After cardiac surgery, paradoxic septal motion is usually present (70). In some patients, septal motion will normalize over a period of months. In patients with significant paravalvular leak, the left ventricle is enlarged and septal motion may become normal or hyperdynamic. In addition,
the left atrium is enlarged. Significant mitral regurgitation secondary to a paravalvular leak is unlikely in patients with hypokinetic or paradoxic septal motion.

**Aortic valve.** Patients who present with an aortic paravalvular leak may demonstrate fine fluttering of the mitral valve or interventricular septum, or both. Premature closure of the native mitral valve in the absence of a prolonged PR interval and atrial fibrillation with long RR intervals suggests severe acute aortic regurgitation (55,56). Generally, mitral paravalvular leaks can be recognized by cinefluoroscopy if there is greater than 9 to 12° rocking of the suture ring (21). With regard to the aortic valve, greater than 6 to 10° rocking is suggestive of a paravalvular leak.

**Ball or Disc Variance (Table 8)**

The older Starr-Edwards aortic valve and the Beall 103 and 104 mitral valves are prone to develop variance. The process of curing the silicon rubber ball was changed in 1965 and ball variance is not seen with the newer aortic

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**Table 7. Echocardiographic Features of Malfunctioning Prosthetic Valves: Paravalvular Regurgitation**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
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<tbody>
<tr>
<td>Short A₂-MVO interval</td>
<td>due to elevated left atrial pressure</td>
</tr>
<tr>
<td>False positive response</td>
<td>left ventricular dysfunction</td>
</tr>
<tr>
<td>Increasing left atrial and</td>
<td>and left ventricular dimensions (volume overload)</td>
</tr>
<tr>
<td>left ventricular dimensions</td>
<td>Normalization of abnormal septal motion or hyperdynamic septal motion</td>
</tr>
<tr>
<td>Fluttering of mitral valve</td>
<td>and/or interventricular septum (in aortic prosthetic valve paravalvular leak)</td>
</tr>
<tr>
<td>Early diastolic “bump”</td>
<td></td>
</tr>
<tr>
<td>Premature mitral valve closure</td>
<td>in acute severe paravalvular regurgitation of aortic prosthetic valve</td>
</tr>
</tbody>
</table>

Abbreviations as before.
Figure 15. Simultaneous electrocardiogram (ECG), phonocardiogram (PHONO) and M-mode echocardiogram in a patient with a mitral Björk-Shiley valve and a significant paravalvular leak. There is abnormal rounding of the initial motion of the disc (wide arrow). In addition, the A2-mitral valve opening interval (MVO) is considerably shortened, measuring less than 0.02 second. A crescendo-decrescendo early short systolic murmur is recorded in this patient. CC = closure click; RESP = respiration.

prostheses. With regard to the Beall 103 and 104 mitral disc variance, abnormal seating of the valve during systole has been reported (6,66,68,71). A shortened A2-mitral valve opening interval and a loud systolic murmur are also characteristic of variance (Fig. 16A).

Cinefluoroscopy is especially useful in documenting systolic sticking or absence of motion suggestive of entrapment of the disc within the valve orifice (Fig. 16B and 17A) (71). The disc may develop erosion and notching, and complete extrusion or disc entrapment can occur (Fig. 16C and 17B). Cinefluoroscopic evidence of Starr-Edwards aortic valve variance includes restriction of motion or extrusion of the poppet or excessive mobility of the cage, or both. With the metallic poppet valves, a radiolucent space may be seen between the metallic poppet and the ring. This is a result of interposition of cloth or intimal proliferation of the suture ring and should not be construed as inadequate seating. Reduction in the aortic opening to aortic closure sound amplitude ratio may be a sign of variance in the Starr-Edwards aortic prosthesis (17).

Dehiscence

Valve dehiscence is caused by disruption of suture lines securing the prosthesis to the sewing bed or by loosening, breaking or avulsing of the sutures from supporting tissue (7). Severe dehiscence results in paravalvular regurgitation or heart failure, or both. M-mode echocardiographic features of dehiscence include detection of the motion of the valve within the left atrium (Fig. 18).

Dehiscence is best evaluated by cinefluoroscopy. Excessive rocking motion beyond the normal range is a characteristic feature. The demonstration of excessive prosthetic mobility, either along the long- or short-axis of the metallic base ring in patients with a bioprosthetic valve, suggests valve dehiscence (7). On occasion, dehiscence can be present in valves with less than 20° rocking motion. However, not all valves with greater than 15 to 20° rocking motion will have significant dehiscence.

Bacterial Endocarditis

The differentiation between a vegetation and a clot on a metallic prosthetic valve is difficult by M-mode and two-dimensional echocardiography. Excessive reverberations and beam width artifacts with two-dimensional echocardiography distract from the clarity of disc or ball motion. However, two-dimensional echocardiography is helpful in detecting vegetations in patients with a bioprosthetic valve (40,41). The echogenic masses can be seen attached to and moving freely with a leaflet. On occasion, a flail leaflet secondary to the destructive process of the infected valve can also be recognized by two-dimensional echocardiography.

Cinefluoroscopy generally is disappointing in detecting vegetations. However, if the vegetations are large enough to interfere with the motion of the valve or produce an aortic root or anular abscess, decreased excursion of the disc or ball or excessive rocking motion may be recognized by cinefluoroscopy.

Mechanical Malfunction

On rare occasions, mechanical malfunction can occur in the absence of fibrous ingrowth, clot formation, paravalvular leak or ball or disc variance. We have encountered two such patients: one with a mitral Björk-Shiley prosthesis and the other with a St. Jude mitral prosthesis. In the latter patient, severe hemolysis and mitral regurgitation were present. At surgery, no disruption of sutures or paravalvular leak was found. Abnormal seating with separation of the
Figure 16. A, Simultaneous left ventricular (LV) pressure tracing, pulmonary venous capillary (PVC) tracing, phonocardiogram and M-mode echocardiogram of a patient with a Beall mitral valve (MV) prosthesis and abnormal seating of the valve. The rhythm is atrial fibrillation. The $A_2$-opening click (OC) interval is variable despite minimal variation of the RR interval. Degree of shortening of the $A_2$-opening click interval is proportional to the height of the $V$ wave on the pulmonary venous capillary tracing. The tallest measured $V$ wave of 98 mm Hg is associated with an $A_2$-opening click interval of 0.02 second. A recording of the echo behind the suture ring in systole may represent cocking of the disc or apparent displacement of the disc behind the suture ring. A systolic murmur is recorded in each cycle length. (Reprinted from Kotler MN et al. [6], with permission.) B, Cinefluoroscopic study during diastole (upper panel) and systole (lower panel). During diastole, the disc seats itself normally, but is shrunk in size. During systole, the disc is in a stuck position producing mitral regurgitation. C, Surgical specimen from a patient with disc variance. The margins are irregular with swelling of the disc.
Primary valve failure is defined as valvular stenosis or insufficiency documented by tissue degeneration without histologic or bacteriologic evidence of infection. Acute mitral regurgitation can develop suddenly and may occur as a result of perforation or tearing of a leaflet (Fig. 19 and 20). Coarse systolic and diastolic fluttering of the porcine valve in the mitral position has been described as diagnostic of a torn or flail leaflet (77). However, aortic insufficiency may also result in isolated fluttering of the mitral bioprosthetic leaflets during diastole. Degenerative changes including thickening or calcification of the valve, or both, are recorded frequently in younger female patients with mitral heterograft valves (78), but can also occur with aortic heterograft valves (Fig. 21). In one study of patients with a mitral porcine bioprosthesis (78), a 70% failure rate was found after an 8 year follow-up period.

Degeneration or Calcification, or Both, of a Prosthetic Valve (Bioprosthesis)

Durability appears to be the greatest problem with all bioprosthetic valves (72–76). A 16% incidence rate of spontaneous degeneration at 7 years has been reported (72).

Figure 17. A, Cinefluoroscopic examination of a patient with a Beall 104 mitral valve showing the disc in a cocked or stuck position (black arrows). B, Pathologic specimen from the same patient with the disc totally immobilized in a semiopen position. The patient died suddenly after experiencing acute pulmonary edema and cardiogenic shock. The disc is irregular and the margin is notched, accounting for the variance.

Figure 18. M-mode echocardiogram of a patient with Björk-Shiley mitral valve dehiscence. The valve motion is recorded well behind the aortic root (Ao) in the left atrium (LA) (white arrow). Valve dehiscence was confirmed by cinefluoroscopic findings of excessive rocking. At surgery, the valve was partially avulsed from the annulus.
Figure 19. Simultaneous phonocardiogram (above) and M-mode echocardiogram (below) of a patient with a flail porcine mitral valve prosthesis. Note the loud crescendo-decrescendo systolic murmur (SM) as well as a mid-diastolic rumble (MDM). In association with the systolic murmur, marked coarse fluttering of the posterior cusp is seen (white arrow). The individual stents are shown (black arrows). IVS = interventricular septum. (Reprinted with permission from Mintz OS, et al. [8], with permission).

Figure 20. Two-dimensional echocardiogram of the same patient as in Figure 19. A, B and C are sequential mid-diastolic, end-diastolic and end-systolic frames of a two-dimensional echocardiographic study from a parasternal long-axis view. Although the leaflets appear normal at end-diastole (B), the tips of the leaflets protrude beyond the plane of the sewing ring into the left atrium (LA) at end-systole (C), indicating leaflet dehiscence (white arrowheads). D, Autopsy specimen demonstrates torn and avulsed leaflets as shown by the probe. LV = left ventricle. (Reprinted from Mintz GS, et al. [8], with permission.)
Figure 21. A and B, Diastolic and systolic frames of a two-dimensional echocardiographic study in the parasternal long-axis view of a patient with calcified and stenotic bioprosthesis in the aortic position (white arrowheads). The systolic frame from the parasternal short-axis view (C) shows marked reduction in the orifice (long arrow) of the aortic bioprosthesis. The patient had a 100 mm Hg pressure gradient across the prosthesis. The operative specimen is shown in D. AVR = aortic valve prosthesis; LA = left atrium; LV = left ventricle; MV = mitral valve; RA = right atrium; RVOT = right ventricular outflow tract. (Reprinted from Mintz GS, et al. [8], with permission.)

Two-dimensional echocardiography is superior to M-mode echocardiography in assessing bioprosthetic valves (40,41). Valve alignment, ring motion and individual leaflet motion can be better evaluated with two-dimensional than with M-mode echocardiography. The individual leaflet motion may not always be adequately visualized by M-mode echocardiography because of transducer angulation and stent alignment.

We especially thank Cynthia Chapman for her administrative contributions.

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