Echocardiographic and Phonocardiographic Characteristics of the Lillehei-Kaster Mitral Valve Prosthesis

By Thomas C. Gibson, M.B. (Cantb), M.R.C.P., Peter J. K. Starek, M.D., Sally Moos and Ernest Craige, M.D.

SUMMARY
The Lillehei-Kaster (L-K) valve is a tilting disc prosthesis currently in use for heart valve replacement. We report data from phonocardiography (PHONO) and echocardiography (ECHO) in 20 patients with a normally functioning mitral valve prosthesis (MVP). The MVP is well recorded by ECHO, resembling a mitral stenosis pattern with a disc excursion of 7 to 12 mm and a mean opening and closing velocity of 37.7 and 59.8 cm/sec, respectively. Combined PHONO and ECHO show that the opening sound of the MVP is small, related to onset of valve opening and not peak opening. It follows the aortic component of the second sound (A2) by 0.05 to 0.09 sec in normals; it may be absent (12/20). Peak opening follows A2 by 0.08 to 0.12 sec. The closing sound of the MVP, best heard in the mitral area, is always two-fold with a small initial high frequency (HF) component and a second large HF sound separated by no more than 0.03 sec. The first component (A) is related to onset of closure and the second (B) to completion of closure. Systolic and diastolic murmurs were commonly present. These data establish the normal ECHO and PHONO findings for patients with L-K MVP. Two other patients are also reported in whom such data were helpful for the noninvasive evaluation of valve function, indicating in one instance acute mitral regurgitation and in the other an increase in degree of aortic regurgitation.

Additional Indexing Words: Mitral valve surgery Prosthesis

The analysis of prosthetic valve dynamics by noninvasive means has become an acceptable way of assessing the functional status of several varieties, notably the Starr-Edwards series. Phonocardiography and, recently, echocardiography have been used for this purpose giving helpful information which can contribute to the identification of malfunction. During the past 18 months, we have been using the Lillehei-Kaster valve, an eccentric monocusp central flow prosthesis. This valve prosthesis is now in general use and, in order to obtain baseline data for the evaluation of function, we have delineated the phonocardiographic and echocardiographic characteristics of the mitral prosthesis. The manner in which certain complications may be diagnosed by those relatively simple methods has also been considered.

Materials and Methods
The study includes 22 patients aged 15 to 63. All had mitral valve replacement for either mitral stenosis or insufficiency but four also had aortic valve replacement. At operation, the mitral valve prostheses were placed so that the major arc of disc pivoting was towards the aortic outflow tract. This corresponds to the normal opening characteristics of the anteromedial cusp of the natural mitral valve. Fourteen patients were studied prior to discharge following operation; the others were seen at a later date.

Phonocardiograms were obtained from the four standard areas on a Cambridge MC IV multichannel data system recorder, using Leatham suction microphones. Simultaneous apex cardiograms and external carotid tracings were also recorded by the same instrument using a Hellige pulse microphone transducer. The ultrasongoscope was a Smith-Kline Instruments Company Ekoline 20A coupled to a Cambridge strip chart continuous recording channel. A 7.5 cm externally focused 2.25 MHz transducer was used and the mitral valve region obtained by scanning in the standard fashion employed by Feigenbaum. It was possible to obtain an echo cardiogram of diagnostic quality in all patients studied. All data were recorded at a paper speed of 100 mm/sec.
In the first five patients studied only polaroid photographs of mitral valve movement were taken. In the remainder it was possible, by means of the strip chart system, to record simultaneously a phonocardiogram from the site of maximal clarity of prosthetic sounds, a mitral valve echocardiogram and a lead II ECG. Thus the identification and measurement of prosthetic valve events was facilitated. Preoperatively, the following phonocardiographic measurements were obtained: 1) Q-S; 2) A2-opening sound. Postoperatively, the following phonocardiographic and echocardiographic measurements were obtained: 1) Q-completion of MVP closure by echocardiogram; 2) A2-MVP opening sound; 3) A2-onset of MVP opening by echocardiogram; 4) A2-peak of MVP opening by echocardiogram; 5) Amplitude of excursion of MVP in mm; 6) Rate of MVP opening and closure in cm/sec, using the line of a slope connecting the onset of anterior or posterior movement with the end of anterior or posterior movement.

All measurements were taken to the nearest 0.01 sec and were a mean of five readings. The measurements were standardized in patients with atrial fibrillation by using cycle lengths in the region of 0.8 sec.

Results

The clinical characteristics of the patients studied and the results obtained are shown in table 1. Two groups are identified for the purpose of analysis. Group A consists of those in whom a normally functioning mitral valve prosthesis was present; assessment of normality was based on clinical grounds with an apparently uncomplicated postoperative course. Examples of recordings taken are shown in figure 1. These data were used to establish the expected normal range. Group B are patients with complications related to prosthetic valve replacement.

Normal Opening Sound

The opening sound of the prosthesis was rarely identified by auscultation. When present, it was heard maximally at the apex or lower left sternal border and was of a higher pitch than an opening snap. It was recorded as a small, discrete single high frequency sound in eight of twenty patients, following the onset of aortic closure by 0.05 to 0.09 sec. It occurred at the onset of prosthetic valve opening, not at the peak, and examples of this sound are shown in figures 2 and 3. The characteristic relationship to mitral prosthesis opening is seen in figure 3. Using the echocardiogram, the time from onset of aortic valve closure to the onset of mitral prosthesis opening varied from 0.05 to 0.09 sec with a mean of 0.070 sec. Peak opening varied from 0.08 to 0.12 sec with a mean of 0.099 sec.

Normal Closing Sounds

Mitral prosthetic closure was heard, usually as a loud, high pitched metallic clicking sound, maximal at the lower left sternal border but well transmitted over the whole precordium. The phonocardiogram demonstrated that two sounds were present. The first (A) was small, usually consisted of several high frequency vibrations, followed by a much larger sound (B) with 2-3 high frequency components lasting 0.02 sec and following A by no more than 0.03 sec (fig. 2). The relationship of sound A to sound B is seen in figures 3 and 4. In these simultaneous phonocardiographic and mitral valve echocardiographic records A is related to the onset of, and B to the completion of, mitral prosthesis closure. The onset of the major component of the closing sound (B) followed Q by 0.06 to 0.08 sec (mean = 0.065 sec). The double sound was present in all patients studied.

Closing Sound Variants

The loudness of the closing sound was inversely related to the preceding R-R interval in patients with atrial fibrillation. This was more apparent for A than B. Figure 5 shows the difference in the amplitude of A and B between a short cycle with R-R interval of 0.62 sec compared to a cycle of 0.95 sec. Following the short cycle, A is six times larger.

Other variants have included a patient who developed a prolonged P-R interval and one with
**Table 1**

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<th>Pt.</th>
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<th>Q-MPC (sec)</th>
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Abbreviations: MS = mitral stenosis; MR = mitral regurgitation; AS = aortic stenosis; AR = aortic regurgitation; SR = sinus rhythm; AF = atrial fibrillation; MPO = mitral prosthesis opening; MPC = mitral prosthesis closure; Amp = amplitude; O Vel = opening velocity; C Vel = closing velocity; * = mitral and aortic prosthesis; — = not recorded.
Illustrating the opening and closing of the Lillehei-Kaster mitral valve prosthesis. A phonocardiogram from the mitral area (PCG-MA) and a lead I ECG were taken. The mitral prosthesis opening sound is shown by the arrow (MPO) and the two high frequency components, A and B, of the mitral prosthesis closing sounds (MPC) are illustrated. Both a systolic murmur (SM) and a diastolic murmur are seen.

Atrial fibrillation who had markedly prolonged R-R intervals intermittently. The patient with first degree A-V block (PR = 0.40 seconds) showed consistently premature prosthetic closure with a clearly defined closing sound (fig. 6). The patient with atrial fibrillation was seen to close his prosthesis prematurely during a particularly long R-R interval (1.39 sec). After 0.50 sec of closure and following the onset of ventricular depolarization the valve opened transiently but closed again almost immediately (fig. 7).

Murmurs
Following mitral valve replacement, it was the rule to hear and record systolic murmurs in group A patients. Generally these were small, in early to mid systole and of medium to low frequency, averaging grade 2/6 in intensity. Examples are seen in figures 2, 3, 4, 7 and 8. Diastolic murmurs following MPO were also commonly recorded in group A but not always heard. They were seen in 14 of the 20 patients. There was some variation in their frequency and examples are seen in figures 1 and 7.

Velocity and Amplitude of Valve Movement
The opening velocity of the normal MVP ranged from 28 to 59 cm/sec (mean 37.7 cm/sec) and the closing velocity from 39 to 99 cm/sec (mean 59.8 cm/sec) immediately after valve closure, but decreasing gradually and reaching a minimum at 0.10 sec. Both systolic and diastolic murmurs were commonly heard at this time.

A simultaneously taken phonocardiogram from the mitral area (PCG-MA), lead II ECG and mitral prosthesis echo-cardiogram. The mitral prosthesis opening sound (MPO) is seen to occur at the onset of the anterior movement of the mitral prosthesis echo-cardiogram. Peak opening occurs 0.04 sec later. The components A and B of mitral prosthetic closure (MPC) are also seen. A systolic murmur is present.
Simultaneous high frequency phonocardiogram from the fourth interspace left sternal edge (LSE-HF), and ECG lead II in the patient with atrial fibrillation. Following the short R-R cycle (0.62 sec) the first component (A) of the second prosthetic closure sound (MPC) is seen to be much greater than that of the longer following R-R cycle (0.95 sec). Component B is also larger although this is less obvious. This patient also had aortic stenosis (SM).

The amplitude of valve movement varied from 7 to 12 mm.

Discussion

Caged ball or nontilting disc mitral valve prostheses usually have clearly identified opening and closing sounds on auscultation. In contrast, the L-K valve does not have an opening sound of any magnitude. When present it is hard to hear, and it is more often absent. As a result, the echocardiogram is the superior marker of opening events for this prosthesis and may be used for accurate timing purposes by the simultaneous recording of a phonocardiogram to identify aortic valve closure. This type of record shows that the opening sound, when present, does not occur at the peak of prosthetic disc opening but at the onset. Therefore, it does not correspond to and cannot be compared with an opening snap or a caged ball opening click, since it is 0.02 to 0.04 sec earlier in timing. A comparison of peak opening for our normal group with data from patients with Starr-Edwards mitral valves shows that the average times from aortic valve closure to prosthetic ball valve peak opening were 0.01 to 0.02 sec longer. This may imply a greater degree of gravitational inertia for the ball than for the disc.

Simultaneous phonocardiogram from the mitral area (PCG-MA), lead II ECG and mitral prosthesis echocardiogram. First degree A-V block (PR = 0.40 sec) is present. Premature closure of the mitral prosthesis is shown by arrow which also indicates the mitral prosthetic closure sound (MPC). S1 is preceded by low frequency sounds and may be an ejection click occurring 0.10 seconds following the onset of the ORS complex. A third sound is also present (S3) and a low frequency diastolic murmur is seen.

Simultaneous phonocardiogram from the mitral area (PCG-MA), lead II ECG and mitral prosthesis echocardiogram. The MPE is not characteristic, showing persistent separation of the posterior (ring) and anterior (disc) echoes. The posterior ring motion at the onset of systole is atypical. During a long R-R interval (1.39 sec) the mitral prosthesis closes partially, indicated by arrow. A small mitral prosthesis closure sound is seen, more characteristic of an A component of the closing sound (MPC). Following the onset of electromechanical systole the mitral prosthesis reopens fully, but closes almost immediately. A systolic murmur is present.
The opening sound of the L-K prosthesis cannot be due to an impingement of the disc on the two retaining struts since this only takes place at full opening. It is more likely related to initial movement of the disc within the two pairs of fulcrum pivot projections of flanges which control the excursional arc. These each extend 2 mm into the valve orifice from the internal surface of the valve housing, with one pair on the outflow and one on the inflow edge. In the closed position, pressures will be equally distributed over the disc, and the onset of a gradient from atrium to ventricle could initially shift the disc onto the outflow projections before pivoting occurred.

The closing sound is made up of two components, the first corresponding to the onset of closure and the second to the end of closure. The second component normally follows the first by no more than 0.03 sec and is the audible closing sound. The interval between the two components roughly reflects the speed of closure of the valve. The time from onset of the Q wave to the completion of mitral prosthesis closure was similar to those reported for the Starr-Edwards prosthesis implying a similar closing velocity.\(^4\),\(^5\)

The first component (A) may be produced in a similar fashion to the opening sound and related to initial disc movements within the four projections already described. This time the disc may impinge on the two projections situated on the inflow edge. The second and major part (B) of the closing sound is made by the disc impinging on the disc stop of the annular part of the valve signifying completion of closure; this is a clear “metallic” click.

It was possible by means of the echocardiogram to measure the amplitude of disc excursion to the nearest 1 mm, the limit of resolution for the 2.25 MHz transducer used, and to establish opening and closing velocities. Amplitude was not necessarily related to valve orifice size nor to the theoretical amplitude of disc movement in vitro. The implication of this discrepancy is not clear although it may be a reflection of the method used to obtain the echocardiogram. The maximal amplitude used for measurement was that found in the standard mitral valve position and the reproducibility with equivalent technique was ± 1 mm in a period of one month following valve implantation. However, we obtained the impression that valve excursion decreased with valve ageing since it was generally less for those which had been implanted for longer than 9 months. Valve velocity was not uniform and varied considerably between patients with apparently normal prostheses. There were also variations in individual patients. However, opening velocities were always slower than closing velocities for any individual patient. This is also the rule of the Starr-Edwards and Beall mitral prostheses.\(^7\),\(^8\) The average opening and closing disc velocities of the L-K valve also exceeded those of the Beall valve.\(^8\)

An interesting feature of the L-K mitral valve prosthesis combined echocardiogram and phonocardiogram was the ability to identify premature valve closure occurring transiently in two patients who had otherwise normal mitral prosthesis echocardiograms and had been included in group A. Originally, certain sounds seen in the phonocardiogram in late diastole were thought to be artefacts. A combined study clearly showed that they were the results of prosthetic valve closure (figs. 6 and 7). It has been hypothesized that the soft first sound in complete A-V block with long P-R intervals was due to floating together of the normal mitral valve leaflets so that there was a short distance for them to travel at the time of closure. The first sound

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**Figure 8**

Simultaneous recording of phonocardiogram (PCG) from aortic area (AA) and fourth left intercostal space parasternal-ly (LSE), apexcardiogram (APEX) and lead II ECG. A low frequency systolic murmur is seen as is a diastolic murmur following a mitral valve opening sound. The apexcardiogram also shows notching of the outward movement phase.
would be louder if the P-R interval were very long (greater than 0.30 sec) because the valve leaflets floated apart again.\(^9\) Such a hypothesis may be examined in the light of our data although it may not be possible to extrapolate from prosthetic disc movement to a normal mitral valve apparatus. In figure 6, it is apparent that the valve closes completely well before the first sound and does not re-open. Thus, whatever the composition of the first sound, it is not due to mitral closure since no mitral contribution is possible. It appears loud, but the loud component is at least 0.10 sec after the onset of electrical systole and could be an ejection sound or a tricuspid sound. However it is unlikely that the latter would be so asynchronous in timing. Further work is required to clarify this point. Figure 7 shows that the mitral valve prosthesis can re-open, given a sufficiently long time for the reversal of an atrioventricular gradient to be overcome, and that the first sound is, as expected, of considerable amplitude.

The L-K valve is a relatively new variant of the single tilting disc prosthesis and little is known concerning its susceptibility to the several problems that have been known to occur in similar prostheses. Paravalvular leakage and infection have already been seen in our own series. Patient 21 was found on the eighth postoperative day to have a grade 3/6 holosystolic murmur at the apex with a reduced aortic valve closure to mitral valve peak opening time of 0.04 sec. These data persisted and we considered that he had a significant paravalvular leak. At cardiac catheterization he had a peak V wave pressure of 30 mm Hg and the left ventricular angiogram showed marked paravalvular regurgitation; this was confirmed at operation. The premature mitral prosthetic opening is consistent with data reported by Willerson et al. in patients with postoperative mitral regurgitation.\(^{10}\) They emphasize that the presence or absence of systolic murmurs may be misleading as an indication of the severity of mitral regurgitation whereas the reduced aortic closure to mitral valve opening interval was the most useful noninvasive measurement in their study. Patient 22 had a delayed aortic valve closure to mitral valve peak opening time of 0.19 sec with slow opening and closing disc velocities. Recatheterization demonstrated that these data were related to severe aortic regurgitation, affecting the prosthesis both mechanically and by increase in left ventricular diastolic pressure. Konecke et al. have recently shown that alterations in the the opening and closing velocities of the intact mitral valve, measured from the echocardiogram, reflect left ventricular diastolic pressure levels.\(^{11}\)

We would conclude that regular follow-up of such patients is necessary in order to identify normal function. This can be done by such noninvasive means as combined echocardiography and phonocardiography since excellent identification of valve dynamics can be obtained. The echocardiogram is especially useful since it may afford the only means of evaluating mitral prosthetic valve opening. Serial data may show significant alterations in valve opening and closing velocity and amplitude. By these means it may be possible to reinforce clinical impressions in patients before their hemodynamic problems become critical.

References
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_Circulation_. 1974;49:434-440
doi: 10.1161/01.CIR.49.3.434

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1974 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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