Valvular-ventricular interaction: importance of the mitral apparatus in canine left ventricular systolic performance

DAVID E. HANSEN, M.D., PETER D. CAHILL, M.D., WILLIAM M. DECAMPLI, M.D., PH.D., DONALD C. HARRISON, M.D., GERALDINE C. DERBY, R.N., R. SCOTT MITCHELL, M.D., AND D. CRAIG MILLER, M.D.

ABSTRACT As the mitral valvular apparatus tenses during systole, forces transmitted along the chordae tendineae to the left ventricular chamber may influence left ventricular performance. To test this hypothesis, 10 dogs anesthetized with fentanyl were studied during cardiopulmonary bypass. The importance of the mitral apparatus in left ventricular systolic function was assessed independent of load by means of the slope of the contractile state–dependent left ventricular peak isovolumetric pressure-volume relationship (Emax), which was measured at constant heart rate and aortic pressure with a micromanometer inside a left ventricular intracavitary balloon before and immediately after all chordae tendineae were severed. Herniation of the balloon was prevented by a disk secured to the mitral annulus. Emax decreased from 11.97 ± 3.35 (±SD) to 6.38 ± 0.96 mm Hg/ml (p < .001) with chordal severing. The volume intercept (Vo) was unchanged. Fluoroscopic studies of the balloon contour in eight additional dogs revealed dyskinesia in the area of the papillary muscle insertion and substantial alterations in chamber geometry during systole after the chordae were severed. Accordingly, we conclude that global left ventricular systolic performance is impaired when chordal attachments of the mitral valve are disrupted. Changes in left ventricular geometry or loss of inward force normally transmitted to the left ventricular wall as the valve tenses may underlie these changes. These findings suggest that postoperative left ventricular dysfunction after mitral valve replacement may be attributable, in part, to excision of the native mitral apparatus at the time of surgery and support efforts to spare chordae during mitral valve surgery.

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CHORDAE TENDINEAE tension\(^1\) and papillary muscle force\(^2\)–\(^4\) increase rapidly during the phase of rapid left ventricular pressure rise in early systole. Conceivably, these forces are transmitted to the ventricular myocardium and influence global left ventricular performance.

This hypothesis has not been tested directly; however, surgical excision of the native mitral apparatus in patients undergoing mitral valve replacement for correction of chronic mitral regurgitation is frequently associated with deterioration of left ventricular ejection fraction.\(^4\)–\(^6\) David et al.\(^7\)–\(^8\) compared preoperative and postoperative left ventricular shortening characteristics in patients undergoing surgical correction of chronic mitral regurgitation by means of three techniques: valve replacement with preservation of the posterior leaflet and its chordal connections to the papillary muscles, valvuloplasty, and conventional mitral valve replacement with excision of the native valve. These authors found that mitral valve excision was associated with a significant decline in left ventricular ejection fraction, which was not observed in either group undergoing chordae-sparing mitral valve surgery. Conflicting results have been reported by other investigators. In the series reported by Lessana et al.,\(^9\) significant decreases in ejection fraction and mean velocity of fiber shortening were observed after valvuloplasty in patients with chronic mitral regurgitation. Furthermore, the postoperative changes in left ventricular shortening observed after surgical correction of
chronic mitral regurgitation are not observed in patients undergoing conventional mitral valve replacement for mitral stenosis. Therefore the importance of the mitral apparatus in left ventricular function is difficult to ascertain from these clinical studies.

Interpretation of these data is difficult, in part, because of the inherent problems in assessing the intrinsic contractility of the left ventricle preoperatively in patients with mitral regurgitation. The extent of left ventricular shortening is influenced by the end-diastolic fiber length (i.e., preload), the force opposing ejection (i.e., afterload), and the contractile state of the ventricular myocardium. In mitral regurgitation, correction of the low-impedance leak into the left atrium increases the net force resisting ejection, which in turn reduces left ventricular shortening. Therefore the mechanical consequences of mitral valve excision cannot be directly assessed in patients with chronic mitral regurgitation when conventional load-dependent methods are used to assess left ventricular function.

In this investigation we analyzed the immediate mechanical consequences of surgically disrupting the chordal attachments of the mitral valve. An intracavitary balloon and micromanometer permitted precise assessment of canine left ventricular performance independent of load, as characterized by peak isovolumetric pressure-volume relationships, before and after the chordae tendineae were severed during cardiopulmonary bypass. These results provide new information on the role of the mitral apparatus in left ventricular mechanics and may have important implications for mitral valve replacement surgery.

Methods

To determine the importance of the mitral apparatus on left ventricular systolic performance independent of load, the slope of the peak isovolumetric pressure-volume relationship (Emax) for well-perfused canine left ventricles was determined in situ at constant heart rate and aortic perfusion pressure with the chordae intact and after excising the chordal connections of the mitral leaflets to the papillary muscles.

Animal preparation. Ten healthy adult mongrel dogs (22 to 31 kg) were anesthetized with intravenous fentanyl (0.75 μg/kg) followed by a maintenance infusion of 0.3 μg/kg/min. Pancuronium (0.1 mg/kg) was administered as needed as a muscle relaxant. This method of anesthesia was chosen because left ventricular contractility remains constant during fentanyl anesthesia. Respiraion was maintained with a Harvard animal ventilator via a cuffed endotracheal tube. A right thoracotomy was performed, the pericardium was opened, and the heart was supported in a pericardial cradle. The right atrium and the ascending aorta (n = 5) or right common iliac artery (n = 5) were cannulated, and the right ventricle was vented. The dogs were then placed on nonpulsatile, normothermic cardiopulmonary bypass (Pemco Corp., Cleveland) with a bubble oxygenator (Harvey H-1300) and crystalloid prime. A catheter inserted into the proximal aorta was connected to a Gould pressure transducer (P231D) and used to monitor coronary artery perfusion pressure, which was kept constant throughout the experiment (range 60 to 115 mm Hg). The mitral anulus and left ventricle were exposed via a left atriotomy posterior to the interatrial groove.

The balloon apparatus used to measure left ventricular pressure-volume relationships is shown in figure 1. To measure and control left ventricular volume, a compliant latex balloon secured to one end of a rigid plastic cannula (id 5 mm) was placed in the left ventricle via the mitral orifice. The pressure response of this balloon was flat and equal to 0 mm Hg up to 50 ml. The balloon volume was varied precisely with warm tap water (37°C) introduced manually with a calibrated syringe. Intraventricular pressure was measured with a micromanometer-tipped catheter (Millar SPC-450, Houston) electronically zeroed in a 37°C temperature bath and calibrated with a mercury manometer. The micromanometer was introduced via a sidearm in the cannula. Balloon herniation through the mitral anulus was prevented by a 25 mm transparent disk located 1.0 cm proximal to the balloon. The disk was secured to the mitral anulus in reversible fashion with eight horizontal mattress sutures (figure 2). In this manner the balloon could be positioned reproducibly within the left ventricle just beyond the mitral leaflets. This relation between the balloon and the mitral leaflets was verified by visual inspection. Total preparation time before initial data acquisition was approximately 90 min.

The pressure signal from the micromanometer was recorded on a Hewlett Packard multichannel recorder system (Model 7758B) at a paper speed of 100 mm/sec at low and high gain for determination of left ventricular peak isovolumetric and end-diastolic pressures along with the electronically determined first derivative of the left ventricular pressure with respect to time (dP/dt), mean proximal aortic pressure, lead II surface electrocardiogram, and balloon volumes. The amplifier response of this system was flat within ±0.5 dB from DC to 50 Hz.

Data collection. Before data acquisition, the balloon volume was increased until the peak isovolumetric pressure generated exceeded 100 mm Hg to maximize the conformity of the balloon to the left ventricular cavity. After ensuring complete oxygen saturation of arterial blood and constant heart rate and aortic pressure, isovolumetric pressure-volume data were obtained at a minimum of five different volumes (range 7 to 24 ml) to generate peak isovolumetric pressures of 50 to 180 mm Hg.

FIGURE 1. The balloon apparatus used to determine left ventricular pressure-volume relationships. The transparent plastic disk located 1 cm from the balloon was used to secure the apparatus to the mitral anulus and to prevent herniation of the balloon into the left atrium after the chordae tendineae were severed. See text for additional description.
FIGURE 2. Cross-sectional view of the heart with balloon apparatus in place. Sutures placed in the mitral anulus were threaded through holes along the circumference of the disk and 2 cm chokers. Mosquito clamps were then used to snug down and reversibly secure the disk in position. Note that the balloon is fastened 1 cm below the disk, allowing imposition of the mitral leaflets between the balloon and disk. Ao = aorta, RV = right ventricle; RA = right atrium; IVC = inferior vena cava; SVC = superior vena cava.

Typically, the associated end-diastolic pressures ranged between 0 and 10 mm Hg.

Data analysis. Left ventricular intracavitary volume was taken as the volume introduced into the balloon plus the small volume occupied by the balloon and plastic cannula. At each volume, the peak systolic pressure was taken as the mean of at least 5 consecutive beats in sinus rhythm. Emax and the volume intercept (Vo) were then computed by linear regression.

Protocol. Initial pressure-volume data were obtained with the mitral apparatus completely intact. The sutures holding the transparent disk were then released, the balloon was removed from the left ventricle, and the chordae tendineae to the anterior and posterior mitral leaflets were severed. The balloon was then repositioned in the left ventricle and the disk resecured to the same position in the mitral anulus. Acquisition of pressure-volume data was then repeated with the chordae tendineae severed. All measurements were completed within 30 min of initial data acquisition. Postmortem examination of the hearts confirmed that the chordae tendineae had been completely severed.

To determine the possible effects of time, anesthesia, and removing the balloon apparatus upon left ventricular contractile state, a total of 11 sham procedures were performed in seven animals (dogs 1, 2, 3, 6, 7, 8, and 9). Peak isovolumetric pressure-volume relationships with the chordae intact were repeated after the balloon apparatus was removed and repositioned in the left ventricle at 10 min intervals.

An additional eight dogs (19 to 32 kg) were prepared in a similar manner to study the effect of the intact mitral apparatus on left ventricular geometry and to confirm the accuracy of the intracavitary volume measurements before the chordae tendineae were severed. In these dogs, the balloon was inflated with a mixture of radiographic contrast material and mineral oil. The unstressed volume of the chamber was measured directly as the maximum volume producing an end-diastolic pressure of precisely 0 mm Hg. Images of the contrast-filled balloon obtained with a portable C-arm fluoroscope and Vidicon tube were recorded at a rate of 60 fields/sec on 1/2 inch video tape (Sony 5800 Video Cassette Recorder). An electrocardiogram QRS analog voltage signal and the pressure output of the micromanometer were digitized simultaneously at 60 Hz with three-digit accuracy by means of a custom-designed analog-to-digital converter and encoded digitally on the video tape to synchronize pressure and fluoroscopic events throughout the cardiac cycle. Fluoroscopic recordings were obtained in six projections (30 degrees apart) around the ventricular long axis with the animal in the right lateral position at a minimum of five volumes as the intraventricular volume was increased stepwise from the unstressed volume. The projections (in animal coordinates) used and the ventricular anatomy in these projections are shown in figure 3. Selected images from these supplementary fluoroscopic studies documented the changes in chamber shape that occurred before and after the chordae tendineae were severed and demonstrate that the intracavitary balloon conformed well to the left ventricular chamber geometry, even in the presence of an intact mitral apparatus. A detailed analysis of these studies of ventricular geometry and regional wall function will be published separately.

Statistical analysis. All results are expressed as the mean ± SD. Student's t test for paired observations were used to assess the significance of differences in continuous data. A p value of less than .05 indicated a statistically significant difference. A distribution-free test for ordered alternatives based on Friedman rank sums was used to analyze the effect of repeated sham procedures on Emax and Vo.

All animals received humane care in compliance with "Principles of Laboratory Animal Care" formulated by the National Society for Medical Research and the "Guide for the Care and Use of Laboratory Animals" prepared by the National Academy of Science and published by the National Institutes of Health (NIH Publication 80-23, revised 1978). The study was approved by the Stanford Laboratory Animal Review Committee.

Results

The results of severing chordae tendineae on left ventricular peak isovolumetric pressure-volume relationships are shown for the 10 dogs along with the group mean results in table 1. In all dogs, Emax decreased, with the mean value falling 47% from 11.97 ± 3.35 to 6.38 ± 0.96 mm Hg/ml (p < .001). Vo was smaller on average after the chordae tendineae were severed, but this difference in Vo was not significant.

Heart rate and aortic pressure were carefully controlled throughout the experiment and remained constant during these measurements. No changes occurred in the electrocardiogram that might have reflected a change in conduction or activation sequence.

Left ventricular isovolumetric pressure-volume relationships obtained from a representative dog before and after the chordal attachments of the mitral apparatus were severed are illustrated in figure 4. Left ven-
tricular peak isovolumetric pressure increased linearly with volume in all cases, with correlation coefficients (r) ranging between .930 and .999 (mean .987 ± .015). The interrupted lines indicate that Vo was determined indirectly by linear extrapolation back to the x-axis intercept. Despite a small decrease in Vo in this example, the pressure generated by the ventricle was greater before the chordae were severed over the range of volumes studied; the difference in pressure-generating potential was more pronounced at larger volumes, reflecting the decrease in peak chamber elastance after the chordae were severed.

This point is further illustrated in figure 5, which shows the original pressure signals from another dog at left ventricular volumes of 11 and 21 ml along with recordings of dP/dt. A significant reduction in pressure-generating potential at equivalent volumes was observed after the chordae were severed. The decline in peak isovolumetric pressure and dP/dt were more pronounced at the larger volume, indicating that a substantial fall in peak left ventricular elastance had occurred. The pressure tracings at high gain show that the end-diastolic pressure at a left ventricular volume of 11 ml equaled 0 mm Hg both in the presence and absence of the intact mitral apparatus; thus, the unstressed volume (11 ml) was unchanged by the chordae severing procedure in this animal. The end-diastolic pressures at the larger volume (21 ml) were also similar for the two conditions; this indicates that severing chordae tendineae had little effect on the passive pressure-volume relationship. Thus, in contrast to the profound alterations in the force-generating capacity with chordae severing, no change in the passive (i.e., end-diastolic) pressure-volume relationships occurred with surgical disruption of the mitral apparatus.

Measurements of the unstressed left ventricular volume were made before and after the chordae tendineae were severed in eight dogs (table 2). The presence of an intact mitral apparatus had no discernible effect on

![Figure 3](http://circ.ahajournals.org/)

**FIGURE 3.** Relationship between ventricular anatomy and the six fluoroscopic projections. A two-dimensional echocardiogram (top) through the minor axis at the level of the papillary muscle insertions is shown as viewed from apex to base with the animal's spine to the left and sternum to the right (i.e., right lateral position). The schematic representation (bottom) indicates the fluoroscopic projections, the locations of the anterior (APM) and posterior (PPM) papillary muscles, and the position of the interventricular septum (stippled area).

![Figure 4](http://circ.ahajournals.org/)

**FIGURE 4.** Left ventricular peak isovolumic pressure-volume relationships before and after chordae tendineae were severed in a representative dog showing characteristic large decrease in the slope (Emax) of these highly linear relationships. The interrupted portion of the line shows the extrapolation to the x-axis intercept (Vo). R = correlation coefficients.

**Dog #7**
TABLE 1
Results of peak isovolumetric pressure-volume relationships in 10 dogs

<table>
<thead>
<tr>
<th>Dog</th>
<th>Emax (mm Hg/ml)</th>
<th>Vo (ml)</th>
<th>HR (beats/min)</th>
<th>Pao (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact</td>
<td>Excised</td>
<td>Intact</td>
<td>Excised</td>
</tr>
<tr>
<td>1</td>
<td>10.9</td>
<td>7.5</td>
<td>4.5</td>
<td>-0.6</td>
</tr>
<tr>
<td>2</td>
<td>10.9</td>
<td>4.6</td>
<td>1.2</td>
<td>1.3</td>
</tr>
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<td>4</td>
<td>13.9</td>
<td>7.4</td>
<td>1.4</td>
<td>-2.5</td>
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<td>6.3</td>
<td>5.8</td>
<td>-6.9</td>
<td>-1.4</td>
</tr>
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<td>10.1</td>
<td>5.3</td>
<td>1.4</td>
<td>-7.5</td>
</tr>
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<td>14.4</td>
<td>7.5</td>
<td>5.3</td>
<td>3.2</td>
</tr>
<tr>
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<td>17.6</td>
<td>5.5</td>
<td>1.5</td>
<td>-5.8</td>
</tr>
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<td>9</td>
<td>15.6</td>
<td>5.6</td>
<td>6.4</td>
<td>-1.6</td>
</tr>
<tr>
<td>10</td>
<td>9.1</td>
<td>6.4</td>
<td>5.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Mean</td>
<td>12.0</td>
<td>6.3</td>
<td>2.8</td>
<td>-0.3</td>
</tr>
<tr>
<td>± SD</td>
<td>±3.4</td>
<td>±1.1</td>
<td>4.1</td>
<td>±4.5</td>
</tr>
</tbody>
</table>

p value <.001 NS NS NS

Data were obtained with chordae tendineae intact and after surgical excision of all chordae.
HR = heart rate; Pao = aortic perfusion pressure.

The unstressed left ventricular volume; the mean value for the unstressed left ventricular volume (9.8 ± 0.9 ml) was actually identical before and after chordal severing.

The results of 11 sham experiments in seven dogs (table 3) demonstrate that Emax and Vo were essentially unaltered by the sham procedures. The determinations of Emax were highly reproducible (r = .843) despite the removal and repositioning of the balloon apparatus, the effects of anesthesia, and the passage of time; this excludes time-dependent deterioration in left ventricular performance as a source of artifact.

FIGURE 5. Effect of severing chordae tendineae on left ventricular pressure generation and dP/dt. Tracings of left ventricular pressure (PLV) at low and high gain along with dP/dt obtained in a representative dog are shown at left ventricular volumes (LVV) of 11 and 21 ml before and after the chordae tendineae were severed.
values of Vo were less reproducible (r = .432); however, consistent changes in neither Emax nor Vo were observed when the sham procedures were performed.

To determine whether the intact mitral apparatus affects left ventricular performance throughout systole, time-varying left ventricular elastance curves were constructed from pressure-volume data obtained during isovolumetric contractions before and after the chordae tendineae were severed. As illustrated in figure 6, left ventricular elastance was greater with the mitral apparatus intact not only at the time of peak isovolumetric pressure generation (i.e., end-systole) but also throughout the cardiac cycle. As in previous studies of ventricular mechanics employing isolated canine hearts,15,16 elastance increased throughout systole until a maximum value (Emax) was reached. Note that the values of Emax determined from analysis of single beats coincided closely with comparable values for this dog determined by the linear regression technique (see table 1). Changes in left ventricular volume (not shown) did not significantly alter the systolic portion of these curves over the range of volumes studied.

The effects of the mitral valvular apparatus on the shape of the canine left ventricle were documented by fluoroscopic recordings in multiple projections. Selected end-diastolic and end-systolic images of the contrast-filled balloon (left ventricular volume 21 ml) are shown side-by-side along with a superimposition of the silhouettes (figure 7). The regions corresponding to the anterior and posterior papillary muscle insertions are indicated in the two projections. With the chordae intact, isovolumetric contraction of the ventricle was associated with little change in ventricular shape, indicating that the force-generating capacity of the ventricular wall was reasonably uniform. In contrast, with the chordae severed, substantial deforma-

**TABLE 2**

Effect of severing chordae tendineae on the unstressed volume of the canine left ventricle (n = 8)

<table>
<thead>
<tr>
<th>Dog</th>
<th>Unstressed volume (ml)</th>
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<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>12</td>
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<td>9</td>
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<td>16</td>
<td>9</td>
</tr>
<tr>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>11</td>
</tr>
</tbody>
</table>

Mean ± SD: 9.8 ± 0.9

p value: NS

Data were obtained with chordae tendineae intact and after surgical excision of all chordae.

**TABLE 3**

Results of 11 sham procedures on the left ventricular peak isovolumetric pressure-volume relationship in seven dogs

<table>
<thead>
<tr>
<th>Dog</th>
<th>Emax (mm Hg/ml)</th>
<th>Vo (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 min</td>
<td>10 min</td>
</tr>
<tr>
<td>1</td>
<td>10.1</td>
<td>10.4</td>
</tr>
<tr>
<td>2</td>
<td>10.9</td>
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</tr>
<tr>
<td>9</td>
<td>10.9</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Mean ± SD: 13.1 ± 3.2

p value: NS

Repeat determinations with the chordae tendineae intact obtained 20 min, 10 min, and just before (0) severing the chordae are shown.

NS = p > .05 for 10 min vs 0 values by paired Student t test (n = 7) and p > .05 for comparison of 20 min, 10 min, and 0 values (n = 4) by Friedman rank-sums test.
tions of these well-perfused ventricles occurred during systole, suggesting a marked heterogeneity of regional force-generating potential. After the tethering effects of the chordae had been surgically abolished, the ventricular wall bulged substantially in the region of the anterior and posterior papillary muscles as the pressure rose within the isovolumetrically contracting chamber. This resulted in an overall lengthening of the minor axis and shortening of the long axis, giving rise to a more spherical geometry at end-systole. Note that this was associated with a 31 mm Hg reduction in the end-systolic pressure generated at the same volume. These changes in ventricular shape were present to a lesser degree at end-diastole. The end-diastolic minor-axis dimension at the level of the papillary muscle insertion increased slightly after the chordae were severed, even at the unstressed volume (not shown), indicating that chordae tendineae tension affects left ventricular geometry, even at low (0 to 8 mm Hg) intracavitary pressures. The changes in left ventricular shape that occurred with chordae severing were confined to the area of the papillary muscle insertions. The contours of the left ventricular intracavitary balloon with the chordae intact and chordae severed are nearly identical in the basal portion of the chamber (i.e., the part containing the mitral leaflets and chordae) at both the unstressed (figure 8) and the maximum left ventricular volume (figure 7); moreover, the images clearly show that the balloon fills the left ventricular outflow tract with the chordae intact, even at low volumes (figure 8). Thus the compliant balloon is not excluded from portions of the ventricle behind the chordae and appears to conform to the geometry of the left ventricular chamber equally well with the chordae intact and chordae severed over the range of volumes studied. Therefore these fluoroscopic studies directly demonstrate the importance of valvular-ventricular interaction to left ventricular mechanics and corroborate that our measurements of pressure-volume relationships were not influenced by nonconformity of the balloon to the chamber geometry with the mitral apparatus intact.

Discussion

This study demonstrates that the complex mechanical interaction between the mitral valvular apparatus
and the myocardial wall substantially enhances left ventricular systolic performance. We found that the slope of the contractile state–dependent peak isovolumetric pressure-volume relationship decreased significantly after the chordae tendineae were severed, whereas the volume intercept of this relationship was unchanged. Marked alterations in left ventricular systolic chamber geometry and dyskinesia in the area of the papillary muscle insertion developed after the chordae were severed. No changes in the peak isovolumetric pressure-volume relationship were observed during sham procedures in which the chordae severing operation was simulated to control for the effects of time, anesthesia, and removing and repositioning the balloon apparatus. We conclude that this deterioration in global left ventricular systolic function was the immediate consequence of surgically disrupting the integrity of the mitral apparatus.

The use of isovolumetric pressure-volume relationships permitted an accurate description of global left ventricular function independent of load. The concept of time-varying elastance has been used to explain the behavior of the left ventricle in terms of a viscoelastic pump.\textsuperscript{15, 16} The instantaneous pressure, $P(t)$, at any time after the onset of contraction, $t$, may be described by the equation:

$$P(t) = E(t)(V(t) - Vo)$$

where $E(t)$ is the left ventricular elastance at $t$, $V(t)$ is the left ventricular volume at $t$, and $Vo$ is the minimum volume required to generate supra-atmospheric pressure. The elastance, $E(t)$, increases throughout systole until a maximum value, $Emax$, is reached.\textsuperscript{12, 15, 16} $Emax$, determined in this study as the slope of the peak isovolumetric pressure-volume relationship, is widely accepted as a load-independent measure of myocardial contractility.\textsuperscript{15-18} The decrease in $Emax$ observed in the present study is characteristic of negative intracavitary interventions such as infusion of propranolol\textsuperscript{17} or reduction of coronary perfusion pressure to induce global myocardial ischemia.\textsuperscript{21}

The finding that $Emax$ was sensitive to surgical disruption of the mitral apparatus illustrates that the peak isovolumetric pressure-volume relationship is not solely dependent on the contractile state of the ventricular myocardium. Although $Emax$ consistently decreased after the chordal attachments of the mitral valve were severed, it seems unlikely that chordae severing caused any injury to the ventricular myocardium or altered the contractile state of the myocardial fibers per se. Rather, we speculate that the net upward forces acting on the mitral leaflets during systole are transmitted along chordae tendineae and increase the regional force-generating potential of the left ventricular chamber where the papillary muscles insert. Surgical disruption of this positive feedback system is detrimental to global left ventricular systolic performance, as manifested in this experiment by consistent reductions in left ventricular chamber elastance (i.e., $Emax$).

This hypothesis is generally supported by our fluoroscopic studies. With the mitral apparatus intact, only minimal changes in ventricular shape were observed during isovolumetric contraction, indicating that the regional forces acting on the chamber were relatively uniform throughout the cardiac cycle. In contrast, chamber geometry changed greatly as the heart contracted isovolumetrically after the chordae were severed, and dyskinesia was observed in the area of papillary muscle insertion. Presumably, these changes are attributable to a reduction in regional force-generating capacity after the forces transmitted to the left ventricular chamber along the chordae tendineae were disrupted. We propose that this loss of regional force generation underlies the decrease in peak left ventricular elastance observed in this study.

An alternative explanation is that the mitral apparatus tethers the left ventricle in an optimal geometric configuration favoring forceful, synergistic left ventricular contraction. The concept of asynchronous contraction, proposed by Rushmer\textsuperscript{22} to explain changes in left ventricular chamber geometry in early systole, includes early contraction of the papillary muscles to pull the atrioventricular ring toward the ventricular apex. This may explain why the longitudinal axis shortens abruptly and the lateral walls bulge outward leading to a more spherical chamber configuration\textsuperscript{23-25} during isovolumic systole. Thus the notion that the chordae tendineae may influence left ventricular geometry is not new; however, our preliminary fluoroscopic studies demonstrate that the mitral apparatus greatly influences left ventricular shape, directly confirming these speculations for the first time. It is conceivable, moreover, that these changes in left ventricular geometry are responsible for the deterioration in global systolic performance observed in this study; that is, the elastic behavior of the left ventricle (i.e., $Emax$) may be dependent in part on chamber geometry. Additional studies are required to determine more precisely the nature of the interaction between the mitral valve and the ventricular myocardium and to distinguish between these possible mechanisms.

Dyskinesia caused by regional ischemia\textsuperscript{26, 27} or dysynchronous activation of the left ventricle\textsuperscript{28} produces parallel rightward shifts in the end-systolic pressure-
Our results relationship.

Summation of these systolic pressure-volume relationship, normal.
to the ventricle pressure-volume predicts results of contracting portion le, intercept. Sunagawa relationship without analogous pressure-volume relationship without.

At end-systole, the pressure-volume relationship for the normally contracting portion of the chamber is the normal end-systolic pressure-volume relationship, but that of the poorly contracting (ischemic) region is probably more analogous to the normal end-diastolic pressure-volume relationship. Summation of these two relationships correctly predicts a parallel, rightward shift in the end-systolic pressure-volume relationship for the total chamber during regional ischemia. Park et al.28 used a similar model to explain their results with ventricular pacing. Our results can also be explained in terms of a two-compartment model in which the ventricle is considered to be composed of a normally functioning element and a dyskinetic element (figure 9). The regional end-systolic pressure-volume relationship for the ventricle distant from the papillary muscle insertion site is relatively normal. In the dyskinetic region, loss of inward force transmitted along the chordae tendineae to the ventricular wall reduces the slope of the pressure-volume relationship without changing the volume intercept. This implies that the net contribution of the mitral apparatus to the force-generating potential of this region is linearly related to volume, which seems reasonable because direct measurements of chordae tendineae tension have shown that it closely parallels left ventricular pressure,3 which is linearly related to left ventricular volume. The resulting end-systolic pressure-volume relationship for the entire left ventricle (figure 9, left panel) has a similar volume intercept, but the slope is intermediate between the slope of the regional pressure-volume relationships. Thus the model is consistent with the results of our study.

Although the methods used to determine left ventricular pressure-volume relationships were similar to those employed in previous studies of left ventricular mechanics using isolated canine hearts,12, 15, 16, 21, 26, 29-33 important differences in our preparation and results must be addressed to fully understand and correctly interpret our data. First, in contrast to the slave dog used in most studies of ventricular mechanics employing isolated canine hearts, cardiopulmonary bypass was used to maintain coronary perfusion in vivo in this intact animal preparation. This method has several advantages. An obvious advantage is that only a single dog is required for each experiment; moreover, since proximal aortic pressure can be carefully controlled, perturbations in contractile state caused by baroreceptor-mediated changes in adrenergic tone34-36 do not influence the experimental results. Baroreceptor-mediated fluctuations in circulating catecholamine levels are not specifically controlled in studies employing slave dogs for the perfusion of iso-

**FIGURE 9.** Two-compartment model of the dyskinetic left ventricle. The left ventricle is considered to be composed of a dyskinetic compartment and a normally functioning compartment distant from the site of papillary muscle insertion. The regional end-systolic pressure-volume relationships for each compartment are shown in the left panel. At end-systole, the pressure-volume relationship of the normally functioning compartment is relatively normal, whereas the slope of the pressure-volume relationship for the dyskinetic compartment is reduced without change in the volume intercept. The resulting end-systolic pressure-volume relationship of the entire ventricle (the sum of the two regional end-systolic pressure-volume relationships) is shown in the right panel along with the relationship before the chordae were severed.
lated hearts. Second, sodium pentobarbital has been used for anesthesia in most studies of left ventricular mechanics employing isolated canine hearts during harvesting of the isolated heart and for the slave dog. The myocardial depressant effects of pentobarbital are well described and may have introduced artifact in the form of a time-dependent deterioration of the isolated heart performance. In the present study, anesthesia with fentanyl was chosen because time-dependent changes in myocardial contractility do not occur with this agent. Last, the mitral valve has been completely excised in previous studies of myocardial mechanics employing the isolated canine ventricle. Excision of the mitral apparatus has been routinely performed because previous investigators did not feel that the intracavitary volume could be measured accurately with the valvular apparatus intact. In the present study, a specially designed device was used that permitted accurate determinations of left ventricular volume even in the presence of an intact mitral apparatus. The fact that the unstressed volume of the left ventricle was unchanged by the chordae severing procedure (table 2) confirms that the chordae tendineae did not render portions of the ventricular chamber inaccessible to the balloon. Although severing the chordae tendineae might alter both the passive (i.e., end-diastolic) and active (i.e., end-systolic) pressure-volume relationships of the chamber, the unstressed volume of the ventricle should be unaffected by chordae severing. Additionally, the fluoroscopic findings demonstrated that the balloon conformed to the ventricular geometry equally well before and after the chordae were severed over the range of volumes used in this study (figures 8 and 9).

Theoretically, if the mitral apparatus had prevented the balloon from filling the entire chamber, the underestimation of the intracavitary volume should be greatest at the lower volumes, since increased pressure would lead to increased herniation around the chordae and to increasingly better fit. This would artifically shift the pressure-volume relationship to the left peripherally at lower volumes, resulting in an underestimation of the slope with the chordae intact. Thus, to the extent that the chordae tendineae rendered portions of the ventricle inaccessible to the balloon, the importance of valvular-ventricular interaction on left ventricular systolic performance was underestimated. Furthermore, obvious departures from the expected linearity of this relationship, which one would expect if the accuracy of the volume determination was dependent on the intracavitary volume itself, were not observed; moreover, the baseline values of Emax determined in our study with the mitral apparatus intact coincide closely with the values of Emax determined in recent studies of the normal ejecting hearts of chronically instrumented, conscious dogs. This supports our contention that the slope of the peak isovolumetric pressure-volume relationship were accurately measured by the techniques used in this study.

The use of a rigid disk secured reversibly to the mitral anulus and the interaction between the intracavitary balloon and the mitral leaflets and chordae may seem somewhat unphysiologic; however, such methods are necessary to study ventricular function immediately after the chordae tendineae are severed. That is, some physical barrier to prevent herniation of the balloon is absolutely required in order to obtain meaningful isovolumetric pressure-volume data. The rigid disk secured to the mitral anulus is somewhat analogous to mitral valve replacement and, therefore, we believe that inferences from this work regarding the effect of severing chordae tendineae on left ventricular function in patients undergoing conventional mitral valve replacement are valid.

Our results indicate that excision of the native mitral apparatus is detrimental to global left ventricular function and may possibly be an important factor contributing to left ventricular dysfunction after mitral valve replacement for chronic mitral regurgitation. We acknowledge, however, that the complex mechanical interactions between the mitral apparatus and the ventricular myocardium of the chronically volume overloaded human heart and the normal canine ventricle may well differ substantially. This concept of valvular-ventricular interaction clearly needs to be studied carefully in man before broad clinical conclusions can be supported.

In summary, this investigation demonstrates that the immediate mechanical consequence of severing the mitral chordae tendineae in normal canine hearts is profound deterioration of global left ventricular performance. The importance of the mitral apparatus to left ventricular systolic performance was manifested by a decrease in pressure generation at equivalent volumes, a substantial reduction in the slope of the left ventricular peak isovolumetric pressure-volume relationship, and the development of dyskinesia in the area of papillary muscle insertion after the chordae tendineae were surgically excised. This occurred in the absence of any discernible injury to the myocardium, supporting the notion that Emax, which is widely accepted as a load-independent measure of contractile state, is not solely dependent on the intrinsic contractile state of the myocardium. The mechanism responsi-
ble for this reduction in peak left ventricular elastance remains to be elucidated fully, but we hypothesize that these changes may be caused by a loss of inward force transmitted to the left ventricular wall or by alterations in left ventricular geometry that promote force generation rather than by a change in the intrinsic contractile state of the myocardium. These findings suggest that left ventricular dysfunction after conventional mitral valve replacement for chronic mitral regurgitation may be attributable in part to excision of the native mitral apparatus at the time of surgery. Chordae-sparing mitral valve surgery may be a rational alternative based on current understanding of the interaction between the mitral valvular apparatus and ventricular myocardium.

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