Anterior Mitral Leaflet Mobility Is Limited by the Basal Stay Chords

Wolfgang A. Goetz, MD; Hou-Sen Lim, MS; Filip Pekar, MD; Hashim A. Saber, PhD;
Patricia A. Weber, DrPH; Emmanuel Lansac, MD; Dietrich E. Birnbaum, MD; Carlos M.G. Duran, MD, PhD

Background—We hypothesize that 2 tendon-like anterior basal stay chords, which remain taut during the entire cardiac cycle, limit the motion of the anterior mitral leaflet.

Methods and Results—Sonomicrometric crystals were implanted in 6 sheep at the insertion of stay chords at anterior mitral leaflet (S1 and S2), papillary muscle tips, fibrous trigones, mitral annulus, and the tip of the anterior leaflet (AL). Distances between crystals were recorded before and after section of stay chords. During the cardiac cycle, the angle α between mitral annulus and AL changed by $+54.2\pm12.4$ degrees; the angles between mitral annulus and S1 ($\beta1$) changed by $+25.7\pm14.6$ degrees, and between mitral annulus and S2 ($\beta2$) by $+20.4\pm7.8$ degrees. During diastole, AL twice crossed the virtual plane formed by the stay chords: during E-wave by a maximum of 6.5 mm (mean, 2.5 ± 2.2 mm) and during A-wave by a maximum of 3.2 mm (mean, 1.7 ± 0.9 mm). After section of both stay chords, total anterior mitral leaflet motion increased as follows: AL, $+6.9\pm3.4$ degrees; S1, $+13.1\pm4.4$ degrees; and S2, $+30.9\pm11.7$ degrees ($P<0.05$).

Conclusions—Although the lateral movement of anterior mitral leaflet is limited by stay chords, the midportion moves unimpaired toward the septum, like a sail, between the 2 stay chords during diastole. A diastolic left ventricular-inflow and systolic left ventricular-outflow funnel mechanism is created. Stay chord section increased lateral anterior mitral leaflet movement. (*Circulation.* 2003;107:2969-2974.)

Key Words: mitral valve ■ dynamics ■ systolic anterior motion

The basal or second-order chords defined by Tandler[1] are those that arise from each papillary muscle and insert into the ventricular aspect of the anterior mitral leaflet. Among them, 2 particularly strong and thick, tendon-like chords[2] insert in a fanlike manner into the undersurface of the body of the anterior leaflet and stretch toward the anterior mitral annulus.[3] In an anatomic study of human hearts, Lam et al[4] found that these 2 chords, termed *principal* or *strut* chords, are the longest and thickest of all chords. Despite their singularity, they have been sectioned, transferred, and assumed to be irrelevant for mitral valve function. The description by van Rijk-Zwikker et al[5] of 2 basal chords that remained taut during the entire cardiac cycle led us to apply the nautical term of *stay chords* because in sail boats, the stays support the mast under any wind direction. Several studies have shown that section of all anterior basal chords or the 2 principal, second-order chords does not result in mitral valve regurgitation.[6,7] However, the anatomic location and unique thickness of the stay chords, which hold the lateral aspects of the anterior leaflet, led us to hypothesize that their presence might control the motion of the anterior leaflet during the cardiac cycle.

Methods

Six adult Targhee sheep (58 ± 18 kg, mean$\pm$SD; Sherick Farm, Missoula, Mont) underwent implantation of 10 ultrasonic crystals under cardiopulmonary bypass (cross-clamp time, 81 ± 24 minutes). Two insulated wires were placed around the stay chords and exteriorized through the left ventricular (LV) wall. After weaning from cardiopulmonary bypass and under stable hemodynamic conditions, baseline recordings were taken, the stay chords were sectioned in the beating heart, and new recordings were taken.

All animals received humane care in accordance with the Principles of Laboratory Animal Care formulated by the Animal Welfare Act in the *Guide for Care and Use of Laboratory Animals* prepared by the Institute of Laboratory Animal Resources and published by the National Institutes of Health (NIH publication No. 85-23, revised 1996). The use of these animals for this research was also reviewed and approved by the Institutional Animal Care and Use Committee of the University of Montana.

Surgical Protocol

Anesthesia and surgical preparation of sheep were performed as previously described.[8] Nine 2-mm ultrasonic crystals (Sonometrics
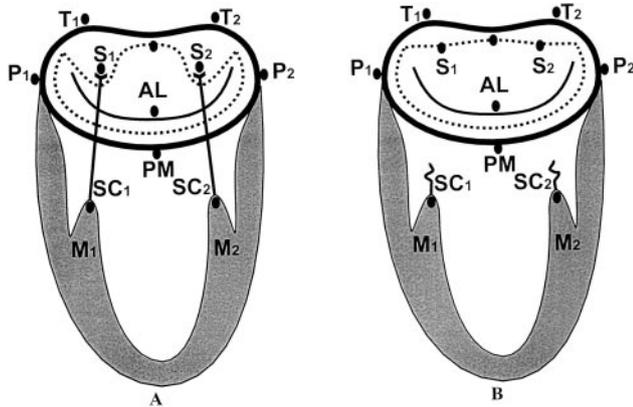
Figure 1. Mitral valve before (A) and after (B) section of stay chords. Solid line, systole; dashed line, diastole. Solid dots indicate crystal location. T1 indicates anterior trigone; T2, posterior trigone; AL, anterior mitral leaflet tip; PM, posterior mitral annulus; P1, anterolateral mitral annulus; P2, posterolateral mitral annulus; SC1, anterior stay chord; SC2, posterior stay chord; S1, insertion of anterior stay chord on anterior mitral leaflet; S2, insertion of posterior stay chord on anterior mitral leaflet; M1, anterior papillary muscle tip; and M2, posterior papillary muscle tip.

Corporation) were implanted and secured with 5/0 polypropylene sutures at the atrial aspect of the insertion points of the 2 stay chords in the anterior leaflet (S1 and S2), both papillary muscle tips (M1 and M2), on the mitral annulus at the midpoint of the posterior and lateral extremities of the mitral annulus (P1 and P2), and at both fibrous trigones (T1 and T2). One 1-mm crystal was placed at the midpoint of the free margin of the anterior (AL) leaflet (Figures 1 and 2).

All electrodes, except those corresponding to the papillary muscle tips, were exteriorized through the left atriotomy. The papillary muscle electrodes were exteriorized through the apex. Two insulated wires were placed around the stay chords close to their leaflet insertion. Both wires were exteriorized through the LV septum and right ventricular outflow tract to prevent injury to other basal or marginal chords. A high-fidelity, catheter-tipped pressure transducer (Model 510, Millar Instruments) was placed within the lumen of the proximal ascending aorta and in the LV cavity through the apex.

After weaning from cardiopulmonary bypass and under hemodynamically stable conditions (at least 30 minutes after weaning from bypass), baseline recordings were taken. Section of the 2 stay chords was achieved in the beating heart by applying diathermia to the 2 wires placed around them. A second set of data were then recorded.

Epicardial echocardiography was performed before and after chordal section to detect the possible presence of mitral incompetence.

Definition of the Phases of the Cardiac Cycle
Geometric changes were time related to each phase of the cardiac cycle, as defined from the aortic and LV pressure curves. End of diastole was defined as the point of increasing LV pressure tracing (dP/dt>0). End of isovolumic contraction was defined as the beginning of ejection at the crossing point of the LV and aortic pressure curves (gradient LV/aorta pressures=0). The dicrotic notch in the aortic pressure curve defined end ejection. E-wave was defined as the first opening motion of the anterior mitral leaflet attributable to passive LV inflow. A-wave, following the E-wave, was defined as the second opening motion of the anterior mitral leaflet attributable to atrial contraction and active LV inflow.[9]

Definition of Anatomic Regions and Angles
The stay chords were defined as the distance between the papillary muscle tips at the origin of the stay chords (M1 and M2) and the insertion point of the stay chords in the anterior leaflet (S1 and S2) (Figure 1). The stay chord plane was defined as the plane between the 2 papillary muscle tips (M1 and M2) and the insertion of the 2 stay chords in the anterior leaflet (S1 and S2). The anterior (T1) and posterior (T2) fibrous trigones were identified by pulling on the midpoint of the anterior mitral leaflet free margin, which created 2 folds terminating at the trigones.[10] The mitral annulus plane was defined as the plane that included both fibrous trigones (T1 and T2) and the middle of the posterior mitral annulus. The motion of the anterior mitral leaflet was defined by the changes of 3 angles during the cardiac cycle: (1) the angle α between the mitral annulus plane and the plane of the fibrous trigones T1 and T2 and the tip of the anterior mitral leaflet (AL), (2) the angle $\beta1$ between the mitral annulus plane and the plane of the fibrous trigones T1 and T2 and insertion S1 on the anterior mitral leaflet, and (3) the angle $\beta2$ between the mitral annulus plane and the plane of the fibrous trigones T1 and T2 and the insertion S2 on the anterior mitral leaflet (Figure 2).

Data Acquisition
Two recordings were taken in each sheep at baseline and after section of the stay chords in the beating heart. Distances between crystals were measured with Sonometrics Digital Ultrasonic Measurement System TRX Series using 10 transmitter/receiver crystals. A postprocessing program (Sonometrics Corporation) was used to examine each individual distance between crystals and for 3D reconstruction of the crystal coordinates.[11] The data sampling rate was 200 Hz. Millar pressure transducer control units (TCB 600) and
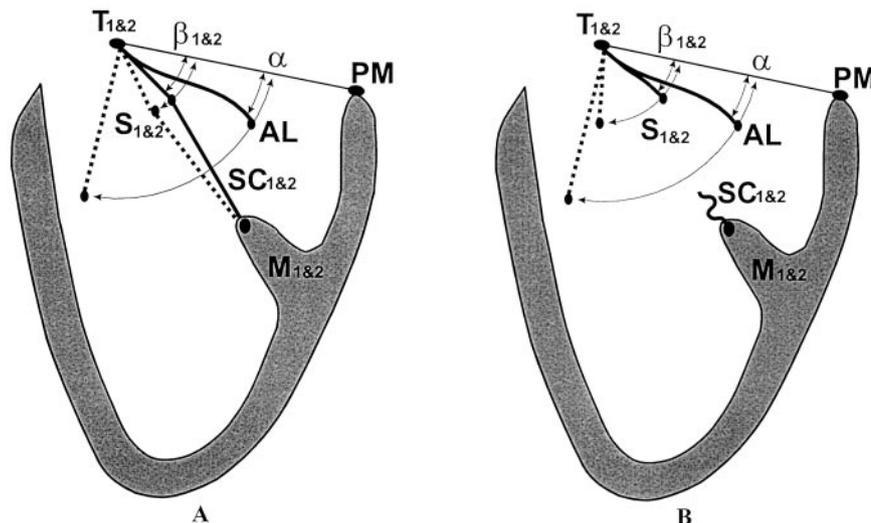
Figure 2. Mitral valve before (A) and after (B) section of the stay chords. Solid line, systole; dashed line, diastole. Solid dots indicate crystal location. T indicates fibrous trigones; PM, posterior mitral annulus; SC, stay chords; S, insertion of stay chords on anterior mitral leaflet; AL, anterior mitral leaflet tip; M, papillary muscle tip; α, angle between mitral annulus plane and mitral leaflet tip; and β, angle between mitral annulus plane and insertion of stay chords on anterior mitral leaflet.

TABLE 1. Hemodynamic Parameters at Baseline and After Section of the Stay Chords

Hemodynamic Measurements	Baseline	After Section
Heart rate, bpm	108.7±14.3	110.1±14.3
Central venous pressure, mm Hg	10.2±1.6	10.8±1.2
Mean pulmonary artery pressure, mm Hg	17.0±3.0	17.3±3.1
Left atrial pressure, mm Hg	9.3±1.2	9.8±1.3
LV systolic pressure, mm Hg	95.5±10.9	97.9±14.1
LV end diastolic pressure, mm Hg	14.8±5.2	16.5±1.6

$P>0.05$.

MIKRO-TIP pressure transducers (Millar Instruments, Inc) were used to obtain the LV and aortic pressures. Pulmonary and left atrial pressures were taken through a 20-gauge needle and a conventional pressure transducer. Epicardial 2D echocardiography with PW- and color-Doppler was used to determine mitral regurgitation before and after section of the stay chords.

Measurement and Statistical Analysis Methods

Distances were explored in a coordinate-independent analysis, using only distance measurements.[12] After close examination of the data, 3 consecutive heartbeats that contained the least amount of noise were chosen for analysis. Summary statistics are reported as mean±SD. Hemodynamic and geometric measures were compared using the 2-tailed t test for paired comparisons (baseline versus chordal section), with a significance level $P<0.05$ (corrected by stepdown Bonferroni for multiple pairwise comparisons). Statistical analyses were done using the SAS/STAT software MULTTEST procedure (SAS Institute, Inc).

Results

All 6 sheep survived implantation of the sonomicrometric crystals and section of the 2 stay chords. Necropsy after euthanasia showed the crystals in the correct position and the stay chords transected approximately 2 to 3 mm from their leaflet insertion into the anterior mitral leaflet. Section of the stay chords did not result in mitral regurgitation (shown by epicardial echocardiography). Hemodynamic measurements taken before and after section of the stay chords did not show significant differences (Table 1).

TABLE 2. Angles Between the Mitral Annulus Plane and the Insertion of the Anterior ($\beta1$) and Posterior ($\beta2$) Stay Chords and the Anterior Mitral Leaflet Tip (α) in Systole and in Diastole at E-Wave and A-Wave

Angle of Mitral Annulus Plane to Anterior Mitral Leaflet	Baseline, degrees	After Stay Chord Section, degrees	Change in Angles, degrees
$\beta1$ end-systole	37.9±11.7	32.8±13.2	−5.1±2.5*
$\beta1$ E-wave	63.6±7.9	71.8±7.4	+8.2±2.0*
$\beta1$ A-wave	63.7±9.7	65.0±7.4	+1.3±2.9
$\beta2$ end-systole	35.9±12.9	17.1±10.7	−17.3±6.7*
$\beta2$ E-wave	56.3±9.7	68.4±12.9	+12.2±3.6*
$\beta2$ A-wave	57.1±11.4	57.5±16.2	+0.5±3.3
α end-systole	19.3±6.0	17.9±6.1	−1.5±0.9*
α E-wave	73.5±12.1	75.8±18.6	+4.5±3.4*
α A-wave	68.9±13.1	69.6±14.1	+0.7±1.8

*$P\leq0.05$.

TABLE 3. Changes in Angles Between Systole and Diastole (E- and A-Wave) at the Insertion of the Anterior ($\beta1$) and Posterior ($\beta2$) Stay Chords on the Anterior Leaflet and at the Anterior Mitral Leaflet Tip (α) With Change in Angles From Baseline to After Section of the Stay Chords

Angle Between Systole and Diastole	Baseline, degrees	After Stay Chord Section, degrees	Change in Angles, degrees
$\beta1$ E-wave	25.7±14.6	39.0±16.6	+13.1 ±4.4*
$\beta1$ A-wave	25.8±18.4	32.2±18.5	+6.5±12.9
$\beta2$ E-wave	20.4±7.8	51.3±14.1	+30.9±11.7*
$\beta2$ A-wave	21.2±9.5	40.4±8.1	+19.2±9.2
α E-wave	54.2±12.4	61.1±14.3	+6.9 ±3.4*
α A-wave	46.8±21.7	51.7±15.8	+4.9±7.0

*$P<0.05$.

Normal Motion of the Anterior Mitral Leaflet

At end systole, the angle $\beta1$ was 37.9±11.7 degrees (Table 2, Figure 2A). It increased during diastole with the E-wave to 63.6±7.9 degrees and with the A-wave to 63.7±9.7 degrees. This corresponded to an increase of +25.7±14.6 and +25.8±18.4 degrees, respectively (Table 3). The angle $\beta2$ was 35.9±12.9 degrees at end systole and increased during diastole with the E-wave to 56.3±9.7 degrees and with the A-wave to 57.1±11.4 degrees, corresponding to an increase of +20.4±7.8 and +21.2±9.5 degrees, respectively. The angle α was 19.3±6.0 degrees at end systole, which was significantly smaller than $\beta1$ and $\beta2$ ($P<0.05$). Therefore, the central part of the anterior mitral leaflet moved closer to the mitral annulus than the lateral aspects of the leaflet did because of the restraining effect of the stay chords (Figure 1a). A systolic LV outflow funnel was formed by the transverse curvature of the anterior mitral leaflet.

During diastole, the angle α increased with the E-wave to 73.5±12.1 degrees and with the A-wave to 68.9±13.1 degrees, an increase from systole of +54.2±12.4 degrees at the E-wave and +46.8±21.7 degrees at the A-wave (Table 3). The diastolic $\beta1$ and $\beta2$ angles were similar, but both were significantly smaller than the α angle during the E- and A-waves ($P<0.05$). Therefore, the anterior mitral leaflet did not move uniformly toward the septum during diastole. Its central part moved unimpeded, whereas its lateral aspects were restrained (Figures 1A, 2A, and 3A). 3D reconstruction showed the anterior leaflet tip moving like a sail between the two stay chords during diastole. When a virtual plane formed by the stay chords (M1-S1 and M2-S2) was constructed, we observed that the tip of the anterior leaflet crossed this plane twice during diastole. After crossing the stay chord plane, the maximum distance between the tip of the anterior leaflet and this plane was 6.5 mm (mean, 2.5±2.2 mm) with the E-wave and 3.2 mm (mean, 1.7±0.9 mm) with the A-wave. Therefore, during diastole, the anterior leaflet tip waves twice between the stay chords. This disparity in the diastolic shape of the anterior leaflet forms a diastolic inflow funnel (Figure 1A).
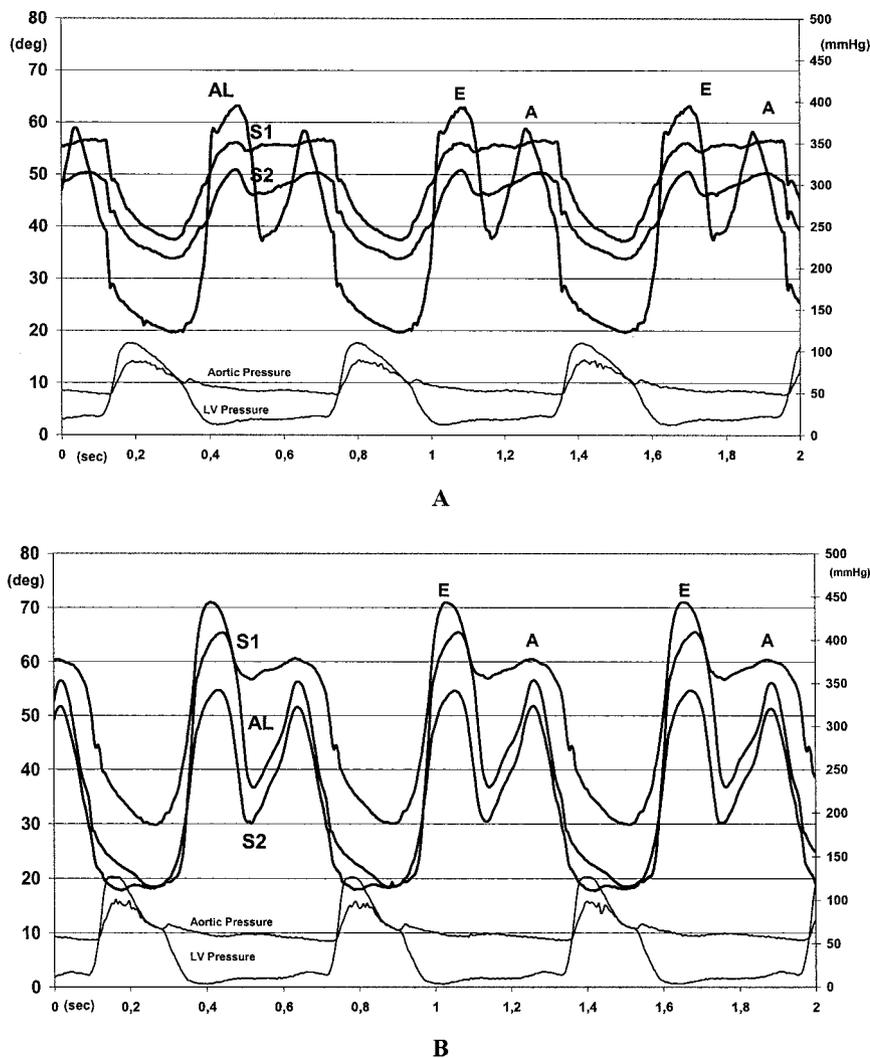
A

B

Figure 3. Sheep No. 6 before (A) and after (B) section of the stay chords. Change in angles between the mitral annulus plane and the anterior leaflet tip (AL). S1 indicates insertion of the anterior stay chord on the anterior mitral leaflet; S2, insertion of the posterior stay chord on the anterior mitral leaflet; E, E-wave; and A, A-wave of diastolic anterior mitral leaflet motion.

Motion of the Anterior Mitral Leaflet After Section of the Stay Chords

After section of the stay chords (Figures 1B and 2B), the systolic angles decreased significantly from their baseline value by -5.1 ± 2.5 degrees in $\beta1$ and by -17.3 ± 6.7 degrees in $\beta2$. The α angle changed by only -1.5 ± 0.9 degrees (Table 2). The distances between the mitral annulus plane and S1 and S2 decreased by -0.3 ± 0.2 mm ($P<0.05$) and -3.1 ± 1.2 mm ($P<0.05$), respectively, although no significant change was measured in the distance between the mitral annulus and the tip of the anterior leaflet. Distances from papillary muscle tips to insertion of the stay chords on the anterior mitral leaflet increased at M1-S1 by $+0.4\pm0.2$ mm and at M2-S2 by $+2.7\pm1.3$ mm ($P<0.05$).

After stay chord section, the angles increased from the baseline value during the E-wave at S1 ($\beta1$) by $+8.2\pm2.0$ degrees, at S2 ($\beta2$) by $+12.2\pm3.6$ degrees, and at AL (α) by only $+4.5\pm3.4$ degrees during diastole ($P<0.05$) (Table 2). Also, the amplitude of the change in angle from end systole to the diastolic E- and A-waves increased significantly (Table 3). The angle $\beta1$ increased during E-wave by $+13.1\pm4.4$ degrees ($P<0.05$) and during A-wave by $+6.5\pm12.9$ degrees. The $\beta2$ angle increased during E-wave by $+30.9\pm11.7$

degrees ($P<0.05$) and during A-wave by $+19.2\pm9.2$ degrees. The α angle increased during E-wave by only $+6.9\pm3.4$ degrees ($P<0.05$) and during A-wave by $+4.9\pm7.0$ degrees. These findings confirm that the stay chords have a restraining effect on the anterior mitral leaflet during diastole, particularly on its lateral portions. Section of the stay chords increased the diastolic excursion of the lateral aspects of the anterior leaflet. Absence of the stay chords resulted in a more homogeneous motion of the whole anterior leaflet (Figure 3B).

Discussion

Transposition of an anterior mitral leaflet basal chord to the free margin is a frequent maneuver in mitral valve repair.[13,14] This technique assumes that the basal chords do not play a critical role in mitral function. Recently, in an acute sheep model, Timek et al[7] showed that section of the 2 main anterior basal chords did not result in mitral regurgitation or altered leaflet coaptation. Only slight changes in the systolic shape of the anterior leaflet were detected. In the isolated working pig heart, Obadia et al[6] have shown that all of the anterior basal chords could be sectioned without impacting mitral competence.

The singularity of the 2 anterior stay chords in terms of their location[3] and thickness[4] made us wonder whether they played a significant role in the mechanism of mitral opening and closure. Furthermore, measurement of their tension in the beating sheep heart has proven to be nearly 3 times higher than their corresponding marginal chord[15] and related with the LV pressure.[16]

As shown in previous studies,[6,7] our data confirm that mitral regurgitation does not acutely appear after section of the stay chords. However, their section induced significant changes in the motion of the anterior leaflet. The normal diastolic motion of the anterior mitral leaflet is not homogeneous. Although the central part of the anterior mitral leaflet moves from its systolic coaptation point to the septum during diastole, the motion of the lateral portions of the leaflet are significantly limited by the presence of the 2 stay chords. During diastole, the anterior mitral leaflet tip balloons toward the septum, like a sail, between the 2 stay chords. The argument that the lateral portions of the anterior leaflet need not move as far as its central portion because the ventricle is circular might be valid, but the fact that section of the stay chords resulted in an increase in their diastolic excursion also remains valid. During diastole, the normal LV inflow becomes funnel shaped, with a transversely curved anterior leaflet whose concavity is toward the mitral orifice. After section of the 2 stay chords, the central and lateral portions of the anterior leaflet move homogeneously, confirming the restraining effect of the stay chords on the normal motion of the anterior leaflet.

During systole, the angle between the central portion of the anterior leaflet and the mitral annulus is smaller than the angles between the lateral aspects of the leaflet and the annulus (ie, an outflow funnel with concavity toward the outflow tract is formed that should facilitate ejection). After section of the stay chords, the lateral portions of the anterior leaflet become as mobile as the central portion.

Our data show that during diastole, the excursion of the entire anterior leaflet becomes more homogenous after section of the stay chords, bringing it closer to the septum. At the beginning of systole, when the mitral valve is still open, the displaced anterior leaflet possibly increases the Venturi effect that facilitates systolic anterior motion observed after mitral valve repair. This possible mechanism suggests an anti–systolic anterior motion function of the stay chords. After reviewing their previously reported data obtained in the isolated pig heart,[6] Obadia recently suggested a similar protective mechanism.[17]

This systolic increase in mobility of the anterior leaflet at the level of the insertion of the stay chords led Messas et al[18] to propose sectioning the stay chords for the surgical treatment of functional ischemic mitral regurgitation. In an ovine model, these authors selectively sectioned the 2 anterior stay chords to abolish their tethering of the body of the leaflet, which increased leaflet coaptation. Additional studies are required before the clinical application of this ingenious technique.

Limitations of the Study

Our conclusions are drawn from only 3 markers on the anterior leaflet. However, the important fact is the relative increase in distances traveled by the central and lateral portions of the leaflet before and after chordal section. Lomholt et al[15] have shown tensional changes on the stay chords following increases in LV afterload and contractility. It is therefore possible that the effects of stay chord cutting might be minimized or increased according to LV status. An additional limitation inherent to sonomicrometry is the presence of electrodes, which might interfere with the normal movements of the structures studied. Additionally, the location of the crystals might vary between animals. Aware of this possibility, all crystals were placed by the same surgeon, and their correct positioning was checked after euthanasia of the sheep.

All data were acquired in an anesthetized, open-chest animal model. Because chordal section was undertaken without a second pump run and immediately after baseline readings, the differences between readings before and after chord transection should be valid. Also, it must be emphasized that findings in sheep are not necessarily applicable to the human. Sheep have relatively few secondary chords in the anterior leaflet, and they are relatively thinner than in the human. Therefore, the role of the stay chords may be more pronounced in humans.

Conclusion

Anterior leaflet second-order stay chords are responsible for the normal nonhomogeneous motion of the anterior mitral leaflet. The lateral portions of the anterior mitral leaflet are restrained by the stay chords, whereas the central portion moves between the stay chords. This nonhomogeneous motion creates diastolic inflow and systolic outflow funnels that, theoretically, should facilitate LV flow patterns. Section of the stay chords results in an increase in mobility of the lateral aspects of the anterior leaflet. Until additional knowledge of the role of the anterior basal chords and especially the stay chords becomes available, a conscious respect for the integrity of the whole submitral apparatus seems warranted.

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