G. Lawrie, M.D.

STRUCTURE, FUNCTION, AND DYNAMICS OF THE MITRAL ANNULUS: IMPORTANCE IN MITRAL VALVE REPAIR FOR MYXOMATOUS MITRAL VALVE DISEASE

Gerald M. Lawrie, M.D.
Methodist DeBakey Heart & Vascular Center, Houston, Texas

Introduction

The first successful open repair of a mitral valve for mitral insufficiency was performed by Dr. Dwight McGoon in 1958.[1] He employed a triangular plication of the prolapsing portion of the posterior leaflet and no annuloplasty. Other surgeons subsequently introduced a variety of techniques.[1-4] Of these, the repair techniques developed by Dr. Alain Carpentier, which incorporated both leaflet repair by a quadrangular resection and annuloplasty, soon proved to be the most effective and reproducible method at that time. Because of the limited knowledge of normal and pathological mitral valve function available in the late 1960s, this repair was based on anatomical and pathological studies obtained through autopsies as well as intraoperatively. While the Carpentier technique continues to be used widely, most centers have found it difficult to repair more than 50-60% of insufficient valves.[5] Only a few centers have achieved higher early success rates. Most have done this by modifications of the classical techniques. Recent reports have documented high rates of recurrence of significant mitral regurgitation in the 5- to 10-year follow-up interval.[6-9]

Our own experience with the Carpentier technique began in 1983. By this time, a growing body of knowledge was accumulating that demonstrated the highly dynamic behavior and important interactions of the six elements of the mitral complex: the left atrium, leaflets, mitral annulus, chordae, papillary muscles, and left ventricle.[10, 11] Because the Carpentier technique uses leaflet resection and rigid or semi-rigid annuloplasty rings, it produces a substantial disruption of these important functions. The mitral annulus is flattened and fully immobilized, and the leaflets also are flattened at their annular attachment. The loss of surface area and distortion of the subvalvular chordae and papillary muscles from the leaflet resection produces diminished or absent leaflet movement. The entire mitral valve is left in a highly stressed state.

In order to overcome these problems, we developed a new technique called the American Correction (Figure 1).[12, 13] The mitral leaflets are never resected, regardless of size. Artificial polytetrafluoroethylene (PTFE) chordae are used to correct localized leaflet prolapse. A full, totally flexible annuloplasty ring is utilized. Most importantly, all adjustments of leaflet position and annular sizing are done during inflation of the heart, with pressurized normal saline delivered at 4 liters a minute into the cavity of the left ventricle. In a controllable fashion, the left ventricular intracavitary and aortic root pressure can be elevated to systolic levels. This produces a series of reproducible changes in the leaflets and annulus that can be correlated with the normally functioning mitral valve in the beating heart (Figures 2-5). The technical details have been reported and are available at www. geraldlawriemd.com.[12, 13]

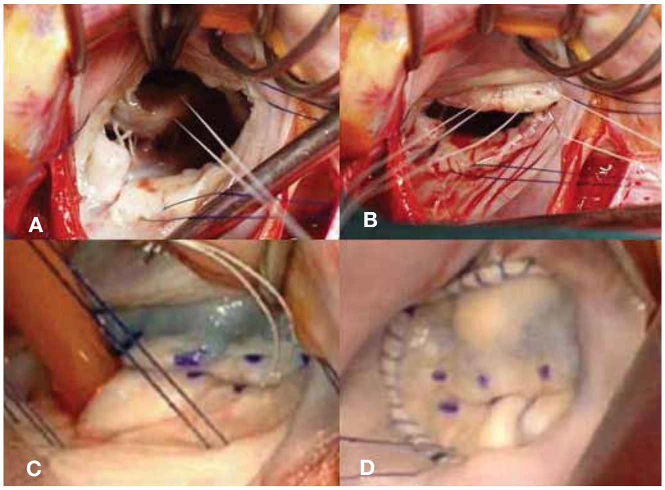

Figure 1. A) PTFE chordae placed in the base of the papillary muscle. B) Chordae are placed through the free edge of the prolapsing leaflet. C) With the left ventricle inflated, the chordal length is adjusted. The annulus is displaced forward to displace the leaflets into the left ventricle. D) The ring is attached. With the left ventricle fully inflated, the leaflets flatten, the saddle shape appears anteriorly, and they descend into the left ventricle.

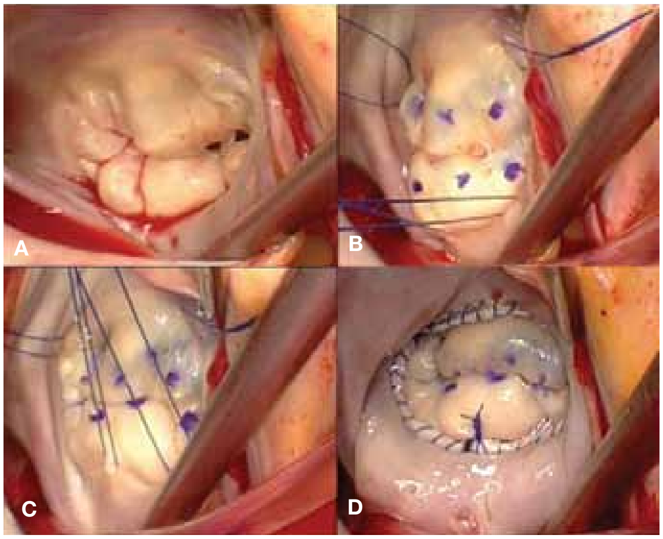

Figure 2. A) Initial appearance of Barlow's myxomatous valve with dilated annulus. B) Dots define the upper edges of the leaflet zones of apposition. Left ventricle is inflated with dilated annulus. Leaflets are prolapsing symmetrically. C) Displacement forward of posterior annulus makes leaflets appose each other and descend into left ventricle. D) Completed repair.

The Role of the Mitral Annulus in Mitral Valve Repair

A detailed understanding of the major role of the mitral annulus in determining the position of the mitral leaflets during the cardiac cycle is essential for successful mitral valve repair. The normal mitral annulus promotes increasing leaflet apposition from the onset of left atrial contraction until the end of systole.[14-20] It influences the shape of the mitral leaflets, especially the anterior leaflet.[17-20] Preservation of this dynamic function is clearly a desirable goal of mitral valve repair. However, the surgical literature generally describes the role of the annuloplasty procedure as static and passive: reinforcement of suture lines, improvement of leaflet coaptation by simply holding the leaflets closer together, and prevention of further annular dilatation. The annuloplasty ring, most commonly rigid, is most often sized from the anterior mitral leaflet or intertrigonal distance — an anatomic rather than functional approach.[3-4]

Structure and Function of the Mitral Annulus

The mitral annulus consists of the condensation of collagenous connective tissue attaching the mitral leaflets and left atrium to the ostium of the left ventricle and aortic root. Although itself a relatively simple structure, it has a complex and varying shape during the cardiac cycle due to its attachment to the muscle of the left ventricle below in its posterior two thirds, circumferentially to the muscle of the left atrium above, and to the aortic root anteriorly. The area of the mitral annulus is reduced by about 25% during late diastole due to contraction of circular muscle fibers in the left atrial wall (Figure 5A, B). Through the aortic-mitral continuity, the anterior one-third of the annulus is attached to the aortic root. This attachment elevates the anterior portion of the mitral annulus as the aortic-mitral continuity swings upward to meet the lower edges of the left and non-coronary sinuses and the interleaflet fibrous triangle. The anterior leaflet portion of the annulus slopes down posteriorly, reaching its lowest level at the line of the mitral commissure that lies at the bottom of this "valley-like" structure. The posterior annulus slopes up slightly as it passes posteriorly but is flatter than the anterior portion. This contour resembles a saddle, with the pommel anteriorly at the aortic root (Figure 3). Thus the anterior and posterior leaflets meet at an angle at the commissure. This angle becomes more acute during isovolumic systole. This change is an important mechanism in the

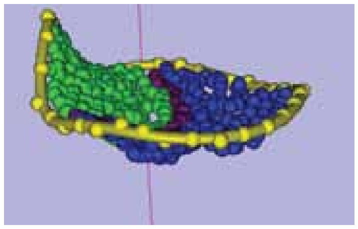

Figure 3. Three-dimensional reconstruction of annulus and leaflets (MDHVC and University of Houston). The pronounced hinge in the annulus between the high anterior (left) and low posterior portions of the annulus (right) is seen. The low valley running along the commissure is marked purple. The anterior leaflet (green) is bent up and blends with the aortic mitral continuity.

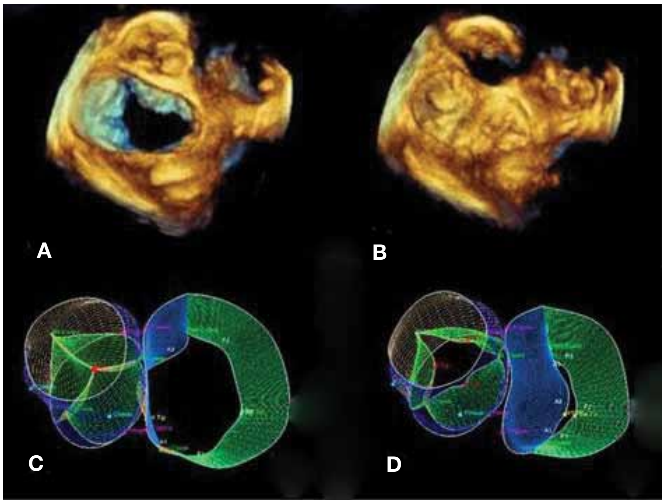

Figure 4. Influence of aortic root expansion on mitral closure. During diastole (A, C) the anterior mitral annulus is almost flat and the anterior leaflet hangs down into the left ventricle. During systole (B, D) the anterior mitral annulus is displaced posteriorly by the aortic root enlargement and the anterior leaflet is elevated towards the left atrium and displaced posteriorly. C and D show diastolic (C) and systolic (D) three-dimensional reconstruction of the interaction of the aortic root expansion and the mitral valve from a 3D echo. (A and B are from an MDHVC 3D echo study; C and D are courtesy of Siemens USA.)

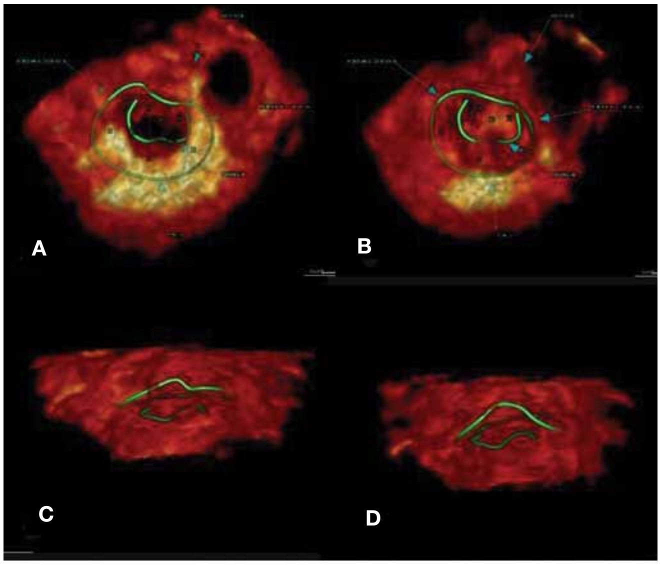

Figure 5. Frames from mitral annular tracking during diastole (A, C) and systole (B, D). The continuous green line is the mitral annulus. The short green line is the approximate position of the commissural line. A and B are shown enface from the atrial side. C and D are anteroposterior views looking from the aortic root through the upthrust anterior leaflet to the posterior leaflet. The systolic reduction in annular area is seen in A and B. The annular folding in the anteroposterior and intercommissural axes is seen in C and D. Also seen is the elevation of the anterior portion of the annulus from aortic root expansion. The entire mitral annulus is displaced downwards in systole (D).

early systolic reduction in the area of the mitral annulus and in promoting leaflet apposition.[21] The expansion of the aortic root during isovolumic systole by enlargement of the sinuses and interleaflet fibrous triangles is a major contributor to this phenomenon.[21, 22] This upward and backwards rotation of the anterior mitral annulus displaces the anterior leaflet posteriorly towards the posterior leaflet (Figures 4, 5). The pronounced folding in the septolateral and intercommissural axes is termed "steepening of the saddle" (Figure 5D). Thus the area of the mitral annulus is reduced by both a sphincter-like mechanism and also a biaxial folding mechanism. The participation of the latter is thought to reduce the extent of the leaflet "wrinkling" that would occur if all the area reduction was from shortening the circumference of the mitral annulus. Left ventricular contraction accounts for another 10-15% area reduction from the effects of contraction of the upper circular muscle fibers of the bulbo-spiralis muscle. The commissural chordae are more numerous, thicker, and shorter than the chordae to the A2 and P2 segments. Thus the A2 and P2 segments and the adjacent annulus rise relative to the commissures during systole, further promoting the steepened appearance of the mitral annulus.

In late diastole, at the start of these area changes, the mitral annulus is mildly elliptical. The short axis of the ellipse reaches a minimum at mid-systole. The annulus becomes progressively more circular through end-systole and diastasis (Figure 5A, B).[14] The mitral annulus ascends toward the left atrium during diastole and toward the left ventricular apex during systole for a total excursion of about 1.5 cm (Figure 5C, D). The annulus also rotates counterclockwise, viewed from above, and is displaced towards the right side during systole. This upward motion displaces a column of blood initially in the left atrium during diastole to a position below the upward-moving mitral leaflets; after mitral valve closure, it is then drawn downwards by the descent of the mitral annulus. The upward motion is atrially mediated, but the downward motion is of ventricular origin and of larger size. The downward motion also augments left atrial filling.

Annular Function in Myxomatous Disease

In patients with myxomatous degeneration of the mitral valve, the size of the mitral annulus is affected by the presence or absence of mitral regurgitation. In its absence, the annulus has relatively normal dimensions or is only mildly enlarged as measured by the circumference and area of the mitral orifice. However, when severe mitral regurgitation is present, the annular area is about double its normal size.[14, 23, 24] In the absence of segmental leaflet prolapse from elongated or ruptured chordae, annular dilation appears to be an essential step in the development of mitral regurgitation in addition to diffuse leaflet prolapse. The dilated mitral annulus is noticeably flatter, and there is attenuation of systolic steepening of the "saddle." The intercommissural angle between the anterior and posterior leaflets is almost flat. The leaflets are also flattened. They touch almost horizontally at their edges in the horizontal plane rather than with the normal 5-10 mm zone of apposition at 90 degrees to the plane of annulus.

Detailed studies have been performed on the effects of annular dilation on leaflet coaptation and leaflet and chordal stresses during the cardiac cycle.[15,16] Annular dilatation produced delay and incomplete leaflet coaptation. When the leaflets do not achieve full coaptation, the stress of resisting the systolic pressure rise is not shared among the leaflets, chordae, and annulus, and extra stress is transferred to the adjacent marginal chordae. Stress magnitudes were observed to have increased more than two-fold on both the anterior and posterior leaflets when the annulus was dilated. This increase in stress was due in part to the stretching by the dilated annulus of the leaflet annular attachments, especially of the posterior leaflet. This annular stretching also causes flattening of the leaflets with subsequent marked increase in leaflet stress.[17] In the study of Kunzelmann et al.,[15] anterior leaflet stress roughly doubled, and stresses were concentrated at the strut chordal attachments and the annulus. The trigones were particularly affected with stresses two- to three-times normal at peak loading. Posterior leaflet stresses increased by fifty fold mainly due to stretching from the dilated annular attachment. Marginal chordal stresses were also examined. The anterior leaflet chordae nearest the midline of the leaflet had stress elevated by 46%. The marginal chordae nearest the commissures had normal stress loading despite annular dilation.

Annular Function in Ischemic Disease

The annular function of patients with functional mitral regurgitation secondary to left ventricular dysfunction differs considerably from those with myxomatous disease.[23,24] They have low ejection fractions and large left ventricular end-diastolic volumes and only mildly enlarged mitral annular dimensions. The mitral leaflet and chordae are normal; however, the annular dynamics are severely impaired. There is more pronounced loss of 3D shape and smaller area changes between systole and diastole. The annulus has the appearance of being pinned down by the poorly contractile left ventricle operating at a high end-diastolic pressure. Unlike myxomatous patients, there is no improvement seen in annular dynamics after restrictive annuloplasty. The annulus remains flat. Thus, again unlike myxomatous disease, in which reduction of the annular circumference with a flexible ring restores a moderate degree of normal shape and dynamic function, there may be a role for rigid-shaped rings in these patients.[20]

Implications for Mitral Valve Repair

The foregoing studies suggest that optimal surgical techniques for mitral valve repair must not only eliminate mitral regurgitation but also leave the mitral valve in the lowest possible state of stress.[20, 25, 26, 31] Myxomatous mitral valves are diffusely affected by the disease. Leaflet failure strength is preserved, but marginal chordae may have as little as 10% of normal strength.[27] Therefore, surgical techniques designed to produce good long-term results must reduce stress on these chordae to prevent future failure. This is important because the most common causes of failure of a repair leading to reoperation are reported to be dehiscence of the rigid ring or leaflet suture lines and "progression of disease" — that is, failure of another portion of the diseased valve. Chordal abnormalities are easily corrected with PTFE sutures. However, lower chordal and leaflet stress are largely dependent on establishing optimal anatomy and physiology of the mitral annulus and leaflet apposition.

Thus, the major goals of surgical ring annuloplasty must be to accurately create the annular dimensions that, in relation to the leaflets, chordae, and left ventricle, provide optimal function of the mitral apparatus. This in turn recreates the full zone of apposition of the mitral leaflets during systole, which restores proper stress distribution. The 25-30% reduction of the mitral orifice area ensures full apposition of the mitral leaflets at the beginning of systole. Sustained leaflet apposition during systole is further facilitated by the fact that the structure of the anterior leaflet is anisotropic in regard to the circumference of the annulus and the radius from the annulus toward the center of the mitral orifice. The anterior leaflet stretches toward the posterior leaflet in early systole and then ceases to deform and becomes rigid.[18] This may in part be mediated by neural activation of the leaflet smooth muscle, which enhances the development of leaflet apposition and leaflet curvature by allowing the systolic increase in annular saddle height and restoration of leaflet billowing.[18] The three-dimensional shape of the annulus has been shown to substantially reduce leaflet stress loadings.[17-20]

Influence of Ring Annuloplasty on Annular Function

The debate about whether to employ fully flexible, semi-rigid, or fully rigid annuloplasty rings is unresolved. The pathophysiological effects of attaching a prosthetic annuloplasty ring to the mitral annulus on the motion of the mitral annulus have been studied extensively. There is a consensus that fully rigid rings totally immobilize the mitral annulus in all dimensions, flattening it completely.[25, 26, 28-31] There is no change in the area of the mitral orifice between systole and diastole. There is no steepening or folding of the annulus during systole. The posterior two-thirds of the annulus is paralyzed, and the posterior leaflet cannot advance toward the anterior leaflet. The annulus as a whole does move toward the apex of the left ventricle in systole and the left atrium during diastole.

Fully flexible rings such as the Duran ring produce some dampening of normal annular motion, but the annulus still displays the changes in geometry and area throughout the cardiac cycle.[30] Our own studies employing three-dimensional transesophageal echocardiography have demonstrated similar preservation of cyclical mitral annular dynamics.[28]

The effects on clinical outcome of different types of rings has been less dramatic. A recent meta-analysis of 478 papers studied the outcome of surgery in patients with different types of rings. There is reasonable consensus from this analysis that post-operative left ventricular function is more normal in patients who received fully flexible rings. These studies have shown preservation to some extent of dynamic mitral area reduction during the cardiac cycle and normal annular dimensional changes. These changes were completely abolished by the fully rigid rings. Clinical outcomes have been similar in most studies with all ring types except for two studies in which the rigid rings were associated with worse late mitral regurgitation.[29] However, late stress-related repair failures were not reviewed.

Worldwide, about one-half of patients with mitral regurgitation do not undergo a successful repair and therefore are not included in these studies. Thus, it is possible that loss of the normal annular changes in dimensions, all of which are directed towards enhancing normal leaflet apposition, could have resulted in failed repairs and conversion to prosthetic replacement in some patients. Furthermore, high rates of recurrent severe mitral regurgitation in the 5-10 year time frame have been reported for the Carpentier technique.[6-9] Stress-analysis studies have shown this to be a highly stressed repair.[17, 20, 25, 26, 31] These subject require further study. Everything we have learned about the mitral annulus suggests that restoration and preservation of normal annular function is critical to achieving high early repair rates and sustained long-term durability.

The American Correction and Annular Dynamics

For more than a decade we have been systematically applying these principles of annular dynamics during surgery for mitral valve repair. The technical maneuvers employed are termed the "American Correction." The "American Correction" is designed to preserve the leaflets and annular function, achieve the correct leaflet zone of apposition of the end of diastole and early systole by means of selection and marking of a predetermined zone of leaflet apposition, and provide correct dynamic annular sizing with a fully flexible ring. This allows the normal diastolic and systolic changes to occur in the annulus and leaflets.

The technique applies to correction of mitral regurgitation from all types of valve pathologies in which adequate leaflet tissue is available. It has simplified repair of patients with anterior leaflet, bileaflet, and Barlow disease patterns.[12, 13] The American Correction has enabled us to achieve 100% reparability of myxomatous and degenerative mitral valve disease in over 1000 consecutive cases. Systolic anterior motion (SAM) of the anterior mitral leaflet is rarely seen; chordal SAM is transiently observed in about 30% of patients. We recently completed our 60th DaVinci robotic repair using these same techniques.

Review of clinical experience over the last 10 years in more than 1,300 patients has demonstrated a very low operative mortality of 0.5% for isolated repair and 2.9% for multiple procedures. Freedom from reoperation at 10 years has been 91% (Figure 6, left). Interestingly, annuloplasty ring dehiscence has not been observed. Echocardiographic studies have shown a low late incidence of 6% for significant recurrence of mitral regurgitation at 10 years (Figure 6, right). This is in contrast to recent reports of results of the Carpentier technique.[6-9]

Summary

Early results of our prospective studies employing intraoperative three-dimensional transesophageal echo have validated these concepts.[28] The weakened but normally functioning chordae are routinely relied upon to maintain long-term leaflet alignment. The substantial reduction in stress levels achieved by accurate annular reduction and good leaflet apposition appear to be

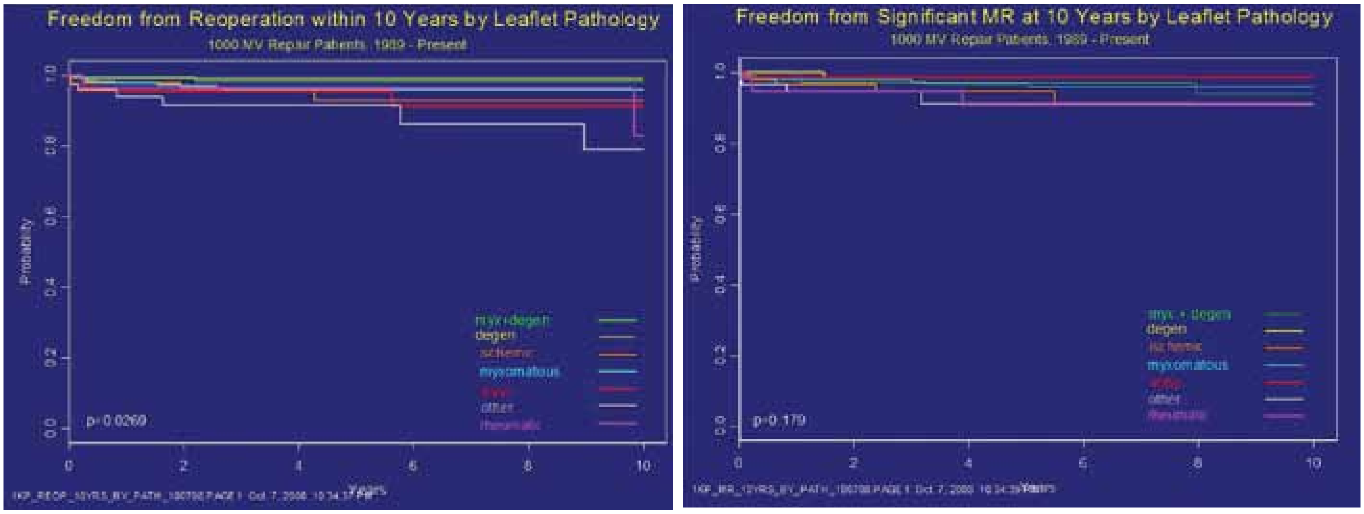

Figure 6. Follow-up data from 1000 consecutive patients who underwent repair of their mitral valves by the "American Correction." Data is shown by Kaplan-Meier analysis for freedom from reoperation and mitral regurgitation according to the preoperative pathology.

critical in ensuring that future problems do not develop. Ongoing three-dimensional echo studies in conjunction with the University of Houston involving pre- and post-operative annular dynamics, leaflet motion and curvature, and stress distribution should yield data that will help us further refine our approach to mitral valve repair.

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