

Techniques of Artificial Chordal Replacement for Mitral Valve Repair: Use in Multiple Pathologic Disorders

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First described by Vetter and coworkers and Frater and coworkers,^{1,2} Gore-Tex (W.L. Gore & Associates, Inc., Flagstaff, AZ) artificial chordal replacement (ACR) has become increasingly popular for repair of mitral valve prolapse.³⁻¹² ACR without leaflet resection can repair virtually all prolapse valves, independent of which leaflet is involved.⁹ Because leaflet surface area is maintained, the majority of valves have no residual leak. Repair failure/reoperation rate has been very low,¹⁰ and chordal replacement is ideally suited for minimally invasive approaches.¹¹⁻¹³ More recently, ACR has played an important role in extending repair to all etiologies of mitral valve disease, correcting defects in chordal structure in rheumatic valves,¹⁴ and endocarditis.^{15,16} In more complex mitral repair, ACR is employed in conjunction with gluteraldehyde-fixed autologous pericardial leaflet augmentation (Adams DH, Rahmanian PB, Chikwe J, et al, video presentation at 2008 Society of Thoracic Surgeons meeting) and full-ring annuloplasty. Using all three methods, virtually all mitral pathologic abnormalities can be repaired,¹⁷ with the benefits of lower operative mortality, no coumadin requirement, excellent durability, improved ventricular function,

fewer valve-related complications, and better late survival, as compared with valve replacement.¹⁸⁻²⁰ The purpose of this article was to review an established method of ACR as an important component of mitral repair by illustrating techniques refined in clinical practice over the past 10 to 15 years. Videos of procedures in this article are posted at JScottRankinMD.com.

General Principles

An experienced intraoperative transesophageal echocardiography (TEE) team is essential for mitral repair, and prophylactic amiodarone antiarrhythmic therapy is employed routinely.^{9,21} Patients with atrial fibrillation undergo a concomitant Cox maze IV procedure.²² With open operations, the patient is approached with median sternotomy, bi-caval venous cannulation, standard cardiopulmonary bypass, cold-potassium cardioplegia, and topical hypothermia using the Daily heart jacket. The latter is especially important for extending safe clamp times for more complex repairs. Left atriotomy is performed in the interatrial groove, and the Cosgrove retractor is used for exposure. The valve is inspected, and the prolapsing segment is carefully identified by injecting cold saline across the valve. This is an important step, because multiple areas are sometimes prolapsing, and missing one can result in repair failure.

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Operative Technique

Mitral Valve Prolapse

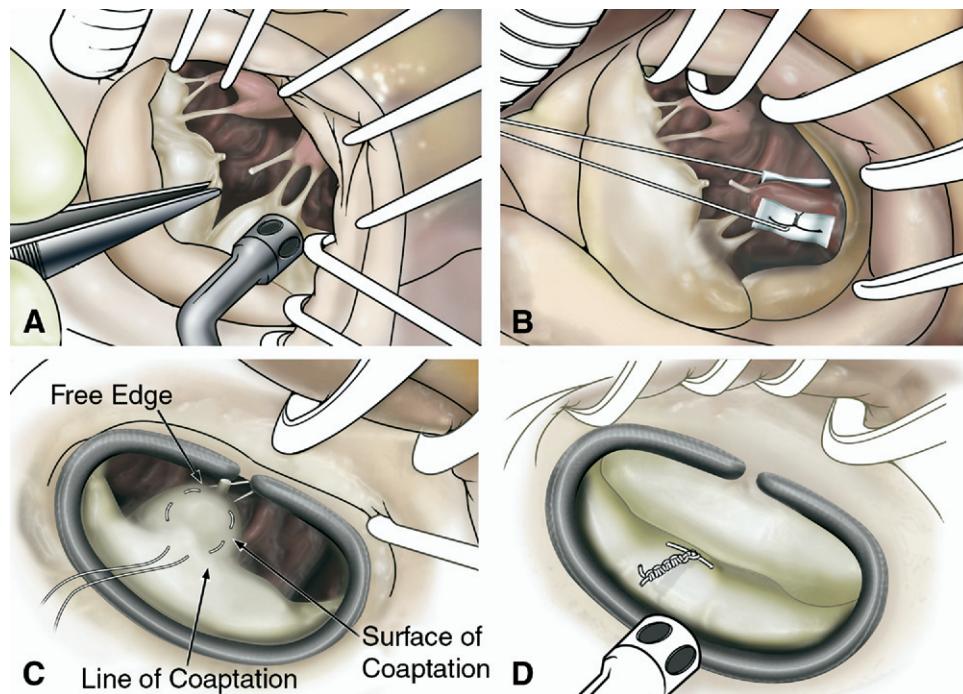


Figure 1 (A-D) Sequential steps in Gore-Tex ACR. For prolapsing segments of the left half of either leaflet, artificial chords are placed to the anterior papillary muscle, and for the right half, chords are placed to the posterior papillary muscle. Artificial chords should not cross each other, or native chords, because they can heal together and interfere with valve function late postoperatively. (A) Ruptured chord from the posterior papillary muscle to the posterior leaflet. (B) As a first step before ring placement, and while exposure of the submitral apparatus is optimal, a pledgetted mattress suture of 4-0 Prolene is placed in the appropriate papillary muscle, oriented longitudinally, and including the fibrous tip of the muscle. A 2-0 Gore-Tex vascular suture (as opposed to 4-0; see Appendix) is passed through the anchor pledget, left untied, and stuffed into the ventricle for later retrieval. The pledgeted anchor suture prevents disruption of the Gore-Tex chord from the papillary muscle. (C) A full rigid annuloplasty ring (CarboMedics AnnuloFlow) is then sutured to the mitral annulus with horizontal mattress sutures of 2-0 Teflon-coated braided suture, buttressed with supra-annular Teflon felt pledges. This interrupted pledgeted suture technique has eliminated ring dehiscence as a cause of late failure. After ring placement, the two arms of the Gore-Tex chord are retrieved from the ventricle and woven into the flail leaflet (straddling the prolapsing segment) in three full-thickness bites: (1) fairly close together in the free edge; (2) flaring laterally in the surface of coaptation; and (3) angling back together through the line of coaptation and onto the atrial surface. This loop pattern stabilizes the lateral aspects of the prolapsing segment, and leaving the suture untied through the anchor pledget allows the two arms to adjust to equal lengths and tensions once the heart starts beating. Weaving the suture from the free edge to the atrial surface produces a “hockey-stick” shape to the leaflet, facilitating the creation of a surface area of coaptation. Again, it is important to take full-thickness bites to prevent subsequent dehiscence from the leaflet, and the Gore-Tex suture is tied over a pericardial pledge if the leaflet is thin.

The knot in the 2-0 Gore-Tex suture is formed initially with two half hitches or a slip knot, and an atraumatic clip is placed lightly on the knot to temporarily fix chordal length. Valve competence is tested by injecting cold saline across the leaflets as gentle traction is placed on the chordal knot and while anterior-posterior and right-to-left leaflet symmetry is observed. If a chord seems too short or long, the clip is removed, and the knot is lengthened or tightened 1 cm. The valve is tested again, and the process is repeated until the leaflets are symmetrically seated into the annular plane and the valve is fully competent. (D) The Gore-Tex suture then is tied tightly against the clip using eight more two-hand square knots. This is important, because tying Gore-Tex off the tissue can increase the chances of unraveling of the knot. The clip is removed and the suture is cut. By “adjusting” the Gore-Tex chords at the end, a symmetrical and large surface area of coaptation can be achieved in every prolapse valve, with complete confidence in excellent physiology, full competence, good leaflet opening, and minimal diastolic gradients.

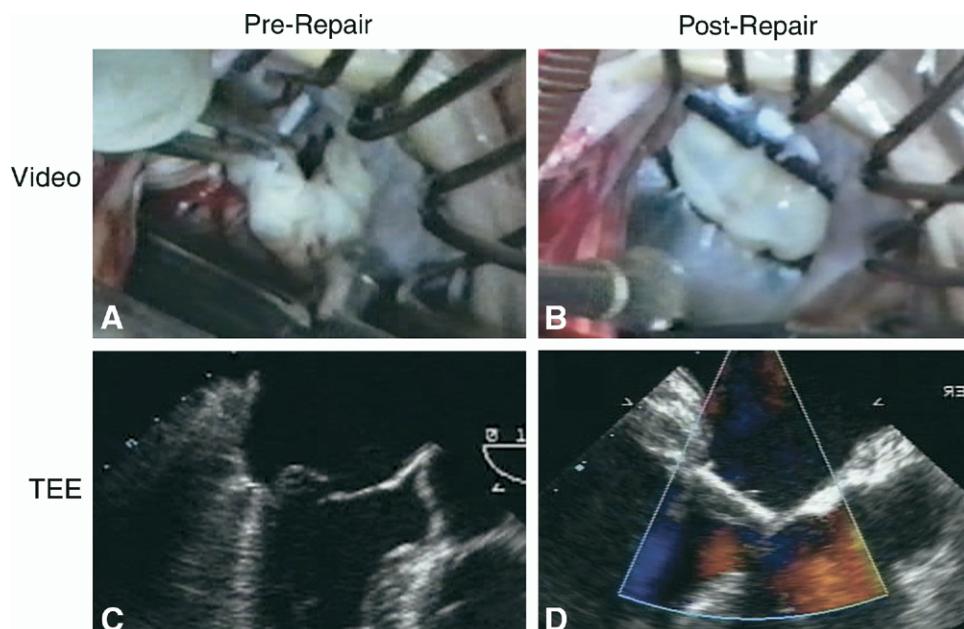


Figure 2 (A) Video frame with posterior leaflet segment prolapsing because of ruptured chord. (B) After ACR and ring placement, the valve is completely competent with cold saline pressurization. (C) TEE appearance of posterior leaflet prolapse. (D) Full competence of the valve after repair. TEE = transesophageal echocardiography.

With the ACR method, systolic anterior motion (SAM) of the anterior mitral leaflet has not occurred, because pulling both leaflets symmetrically down into the ventricle holds the anterior leaflet out of the outflow tract and prevents SAM. Leaflet tissue is *never* resected. The anterior and posterior leaflets are shaped differently but have the same surface area.²³ Resecting posterior leaflet creates a relatively redundant anterior leaflet, predisposing to SAM. Sliding plasty can compensate by pulling the reconstructed posterior leaflet down into the ventricle. However, the easier solution is not to resect leaflet, especially because maintaining surface area promotes competence. Small leaflet clefts are closed (only if necessary) with figure-of-eight sutures of 5-0 Prolene. Again, ACR without leaflet resection produces no residual leak in 95% of prolapse patients, and mild leak in only 5%.¹⁰ In mitral prolapse, virtually 100% of valves can be successfully repaired using ACR, independent of the anatomy and with negligible early or late conversion to replacement.⁹

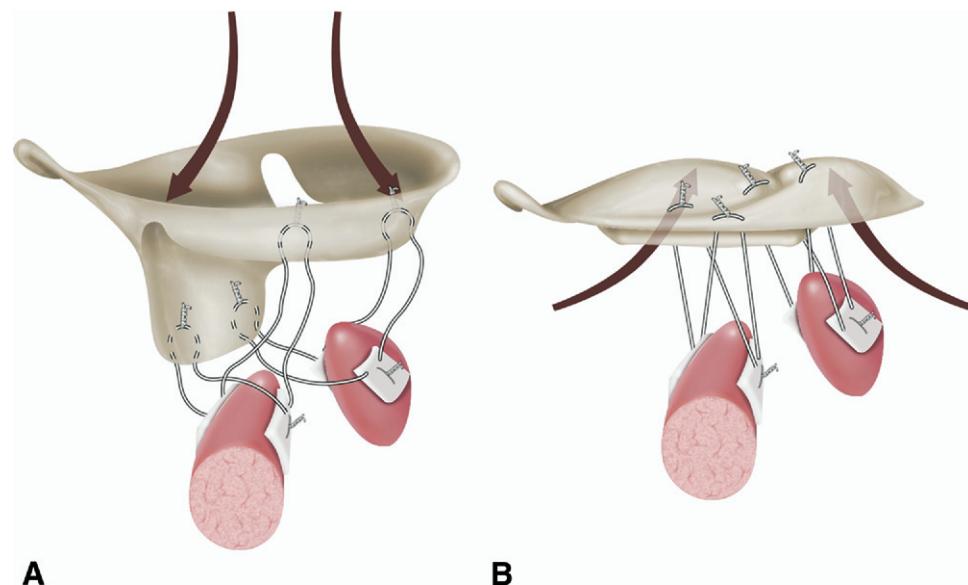
Generalized Prolapse: Barlow's Valves

Figure 3 (A) Diastolic and (B) systolic appearance of a Barlow's valve after ACR repair. Note artificial chords to the left half of both leaflets are placed to the anterior papillary muscle, and the right half to the posterior papillary muscle. It makes little difference what part of the valve is prolapsing. Anterior leaflet prolapse is repaired as easily as posterior prolapse, and in a Barlow's valve with generalized prolapse, employing four independent sets of chords (that can be adjusted individually at the end of the procedure) allows successful repair, even in the most complex anatomies. The authors believe it is important to not have multiple points on the leaflet connected to the papillary muscle with a single Gore-Tex suture. At most, four to five independent chords are required, allowing individual adjustment of chordal length at multiple points on the leaflets and perfect symmetry of repair. Finally, more unusual prolapse pathologic defects such as commissural prolapse or prolapse of multiple different scallops can be repaired easily and reproducibly. Because the repair is not based on myxomatous chords (which can predispose to late chordal rupture²⁴), and because chordal support is actually augmented by the Gore-Tex material, the late failure/reoperation rate has been exceedingly low (2 to 3% over 10 years of follow-up).¹⁰ The subsequent endocarditis rate has been around 1% (a real advantage of repair over replacement), and moderate mitral regurgitation recurrence treated medically has occurred in less than 2%. Together with an operative mortality approaching zero,¹⁷ ACR currently is producing early and late results in mitral valve prolapse equivalent to correction of adult atrial septal defect.

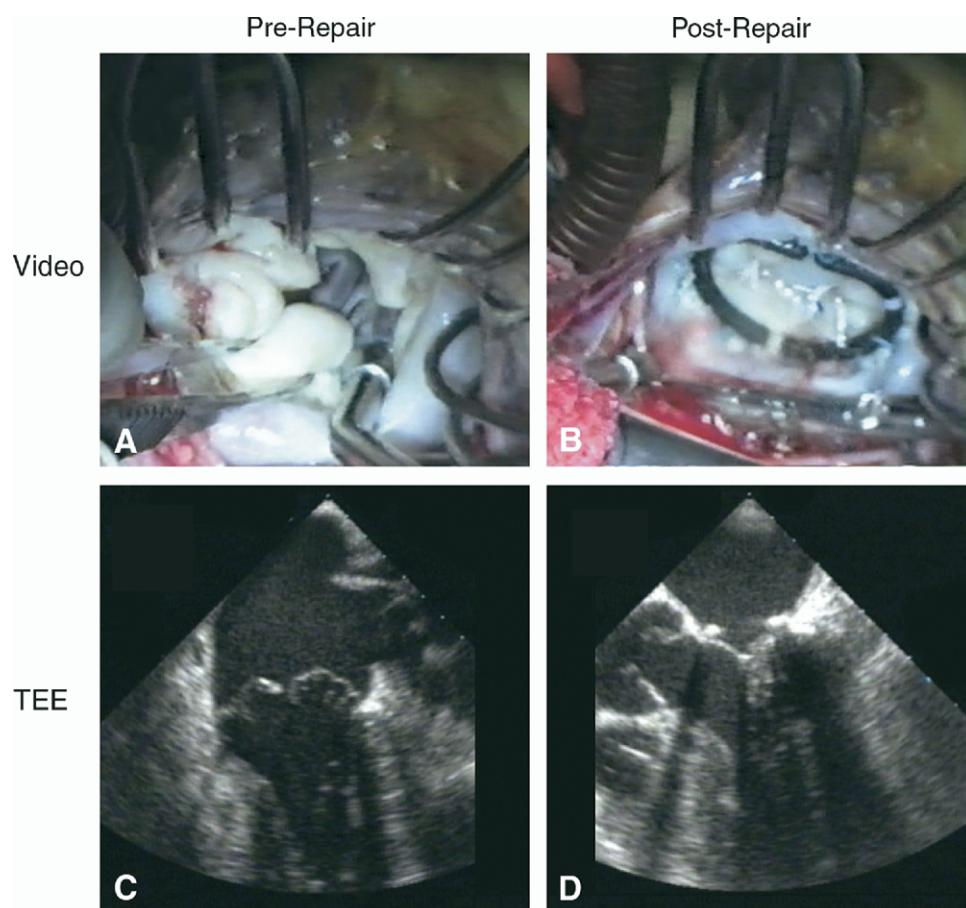


Figure 4 Video frames and TEE appearance of a Barlow's valve with generalized prolapse and scalloping, before (A, C) and after (B, D) four-chord ACR. Good anterior-posterior and left-to-right leaflet symmetry was achieved with a fully competent valve. TEE = transesophageal echocardiography.

Robotic Repair



Figure 5 Setup of the DaVinci robotic system for mitral repair with four arms and a working port in the center. ACR is ideally suited for use with minimally invasive approaches. In the past several years, our group has made the transition to employing the DaVinci robot to repair most patients with isolated posterior leaflet prolapse, which comprises approximately half of prolapse cases.

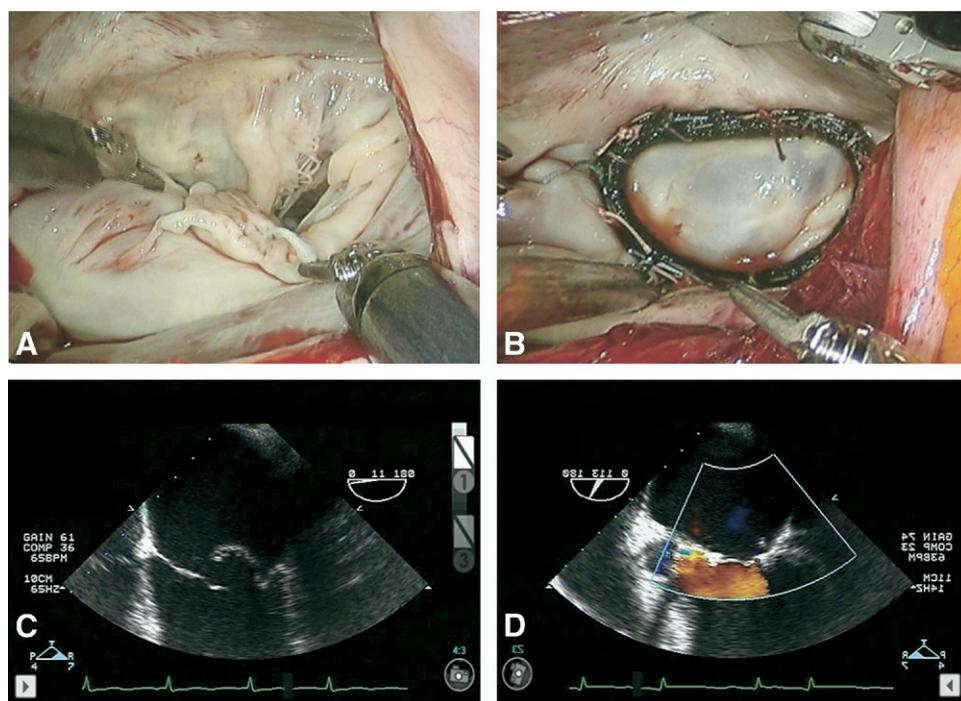


Figure 6 (A-D) Ruptured chords to the posterior leaflet before (A), and after (B), robotic repair with corresponding TEEs (C and D). The posterior leaflet is flail at baseline; after ACR repair, the valve is fully competent. Using the robot, chordal insertion with ring annuloplasty but without leaflet resection is a simple procedure. ACR is performed in exactly the same fashion as open repairs, except exposure of the submitral apparatus actually is better, and the patient experiences less incisional pain and morbidity. At present, increasingly difficult repairs are being performed with this technology, involving multiple chords or other aspects of the technique described above, and it is likely that robotic procedures will be used in a larger percentage of patients over time.¹³

Ischemic MR and Pure Annular Dilation

Most patients with postinfarction ischemic MR can be managed with full ring annuloplasty alone.^{20,25-27} The important concept is reduction of the anterior-posterior mitral dimension,²⁸ which is best accomplished with a full rigid or asymmetrical ring.²⁹ Effective repair in ischemic MR reduces operative mortality and improves late survival as compared with valve replacement.^{20,30} Rarely, patients will manifest elongation or rupture of a papillary muscle infarct, producing leaflet prolapse. In these cases, ACR can be used together with ring annuloplasty to repair the pro-

lapse. It is important to note, however, that the chords should be placed to a viable papillary muscle, because the infarct area can expand later and tether the leaflet if the chord is attached to the infarct. Patients with poor ventricular function or leaflet tethering preoperatively are treated with a posterior leaflet pericardial patch (see below) to compensate for the tethering.³¹ Of course, patients with pure annular dilation, as encountered most often in females with hypertensive or other types of cardiomyopathies, do very well with ring annuloplasty alone and do not require ACR.³²

Rheumatic Disease and Endocarditis



Figure 7 Artificial chords have facilitated repair of rheumatic valves and endocarditis. When combined with gluteraldehyde-fixed autologous pericardium to augment defective leaflets, along with ring annuloplasty to address annular pathologic abnormalities, ACR allows repair of virtually all mitral disorders. In rheumatic disease, repairs previously failed for two reasons. The first is the almost uniform finding of a scarred-retracted posterior leaflet in rheumatic valves. The second is immobility of the anterior leaflet due to submitral chordal thickening and/or calcification. Correction of the first problem is begun by first performing a generous decalcifying commissurotomy, and then the posterior leaflet is incised 2 mm from the annulus throughout most of its length. A gluteraldehyde-fixed autologous pericardial patch is inserted into the posterior leaflet with a 5-0 Prolene running suture, significantly augmenting posterior leaflet surface area (shown above). This procedure was originally described by Frater,³³ and then by Carpentier's group,^{34,35} and is much easier than one might anticipate. A similar technique can be used for the anterior leaflet, when necessary.³⁶

The anterior leaflet/submitral pathologic abnormalities of rheumatic disease are addressed by resecting the primary and secondary chordal attachments of the anterior leaflet to both papillary muscles.¹⁴ Any calcium usually is located in the superficial layers and can be debrided easily. With careful effort, a fairly normal-appearing anterior leaflet emerges, with a good “hinge” or “trap door” mechanism. Occasionally, the thickened and fibrotic chordal insertion sites on the underside of the leaflet can limit mobility, and these are excised with sharp dissection. After a highly mobile anterior leaflet is created, it is reattached to the papillary muscles by running a Gore-Tex artificial chord from the left-front corner of the rectangular anterior leaflet to the anterior papillary muscle, and from the right-front corner to the posterior papillary muscle (above).

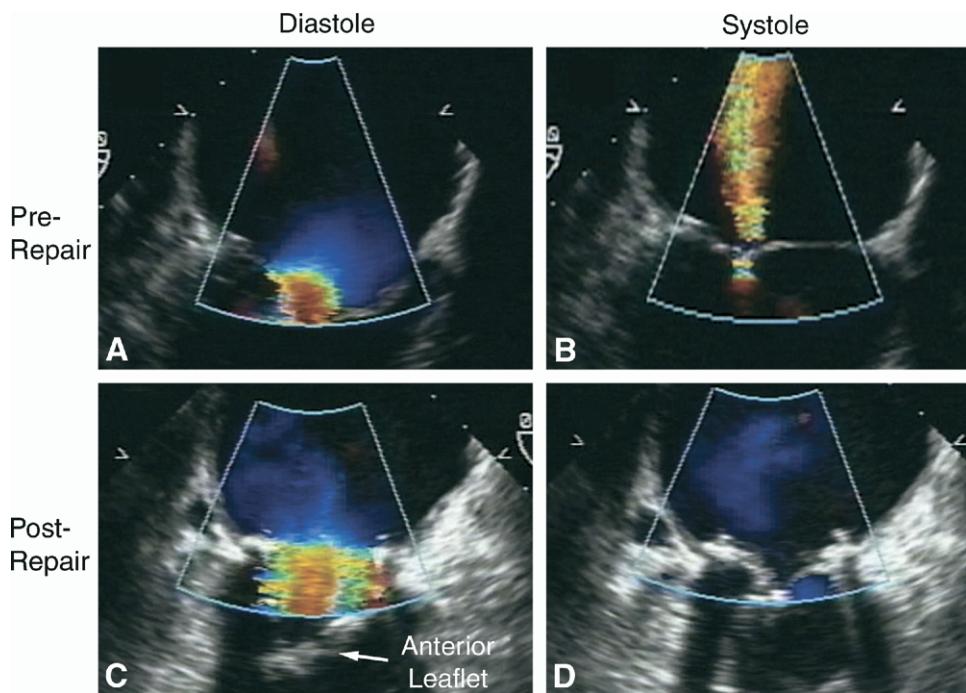


Figure 8 Diastolic (A, C) and systolic (B, D) TEEs of a calcified mitral valve with rheumatic stenosis and insufficiency before (A, B) and after (C, D) repair. Two artificial chords reattached the anterior leaflet to both papillary muscles. The valve opens well with a laminar flow pattern, and incompetence has been eliminated. With this repair, the posterior leaflet usually acts as an immobile buttress for anterior leaflet coaptation, and most of the valve function occurs in the anterior leaflet. Early and intermediate-term results have been excellent, but definitive conclusions as to full applicability await longer follow-up.¹⁴ However, it is now quite common to operate on patients with calcified, stenotic, and insufficient rheumatic valves in chronic atrial fibrillation, and to end up with repaired valves functioning normally, with sinus rhythm (after the Cox maze IV procedure), and with the patient receiving only aspirin anticoagulation—a truly gratifying outcome. Similar repairs are used for endocarditis, employing pericardial patches and Gore-Tex artificial chords to restore the valve to normal function. Of course, long-term outcomes in endocarditis are limited by possible recurrent drug use, etc. However, ACR is an essential component of mitral repair currently performed for both rheumatic disease and endocarditis.

Conclusions

Artificial chordal replacement is now a mainstream technique in mitral valve repair. ACR has not only increased the applicability and early/late success rates of repair for prolapse but has opened up other mitral disease etiologies to the routine benefits of repair. Long-term data now are available to document the stability of this approach and to justify its increased application to most mitral pathologic defects. Last year in North America, 70% of isolated mitral valve procedures were repair, and to the benefit of the patient population, this trend continues to be positive.³⁷ Little question exists that the technique of artificial chordal replacement has contributed to this trend, and we may be entering an era in which prosthetic mitral valve replacement becomes rare. Mitral valve surgery, once the high-risk procedure in cardiac surgical practice,³⁸ now is one of the most gratifying, due in part to the emergence of mitral valve repair and artificial chordal replacement.

Appendix

One of the late repair failures in our series, over 10 years ago, was due to rupture of 4-0 Gore-Tex chords placed to an anterior leaflet 3 years earlier. The valve was re-repaired with 2-0 Gore-Tex suture, passed from the same anchor pledges

to the anterior leaflet, and adjusted to proper length. At that point, we changed to 2-0 Gore-Tex for chordal reconstruction and have not experienced any more chordal ruptures. Moreover, the 2-0 Gore-Tex has functioned well, with no leaflet immobility or other problems observed. The 2-0 Gore-Tex is a little “spongy” and requires care in tying tightly, as described above. It has been used routinely for the past 10 years.

When the 4-0 Gore-Tex chord failed, the following “back-of-the-napkin” analysis was performed. Pressure, of course, is force per unit area, and the force encountered by chords to a large anterior leaflet would be higher at a given pressure than those to a smaller posterior leaflet. As a worse-case calculation, a 250 mmHg pressure in the left ventricle at 1333 dynes/cm²/mmHg would produce a pressure of 333,306 dynes/cm². A no. 36 Carpentier ring has an area of 5.85 cm², and assuming a similar area of the anterior leaflet, the total linear force on the anterior leaflet would be 1,933,166 dynes or 1.97 kg. It is unclear how much of this force would be supported by the annular attachments of the anterior leaflet, but if one assumes very little, the total worse-case force subjected to an artificial chord supporting a large anterior leaflet would approach the yield force of 4-0 Gore-Tex, which is 2.03 kg (Jim Silverman, W.L. Gore & Associates, Inc., Flagstaff, AZ, unpublished data). The yield force of 2-0 Gore-Tex

is 3.49 kg (Jim Silverman, W.L. Gore & Associates, Inc., Flagstaff, AZ, unpublished data), and thus, an almost twofold margin of safety exists with the larger suture.

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