Evolving Concepts and Technologies in Mitral Valve Repair

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Over the past few decades, it has become apparent that mitral valve repair is preferable to mitral valve replacement for the majority of patients undergoing surgery for mitral regurgitation (MR). The advantages of mitral valve repair include low rates of thromboembolism, resistance to endocarditis, excellent late durability reported for as long as 25 years, and no need for anticoagulation in the majority of patients.1–5 Because of these advantages of repair over replacement, the threshold for performing mitral valve repair has been lowered to include patients with MR who have early symptoms or even those who are asymptomatic, assuming that the chance of successful repair is ≥90% according to the latest American College of Cardiology/American Heart Association guidelines.6,7

Recently, surgeons have evaluated new techniques to further improve mitral valve repair, and cardiologists and surgeons are increasingly interested in the potential for percutaneous approaches to mitral valve repair.8 Myxomatous MR affects 1% to 2% of the population and therefore is a common pathology for mitral valve surgery, but the complexity of the operation may be difficult, which leads to generally low rates of repair. In a recent review, only 44.3% of patients in the United States who required mitral valve surgery for MR received a mitral valve repair,9 and in the Euro Heart Survey, repair rates were similarly low (46.5%).10 The goals of mitral repair are to maintain leaflet mobility, remodel the annulus, and allow normal coaptation of the anterior and posterior leaflets.

Recent advances in techniques and new concepts for mitral repair are important to cardiologists and other clinicians interested in the management of patients with mitral valve disease. Accordingly, an improved understanding of these concepts will aid in the development of innovative techniques to create safe, durable, reliable, and reproducible mitral valve repair techniques, both by open and by less invasive surgical methods. Many of these concepts may be applicable with novel percutaneous approaches.11–14 We aim to clarify these concepts and techniques in this review.

Mitril Valve Structure and Function

More than 30 years ago, detailed quantitative assessments of normal mitral valve morphology for each component of the mitral valve complex were performed15,16 and have been updated in the contemporary cardiology literature with in vivo imaging.17 Other techniques include finite element computer modeling,18,19 3-dimensional (3D) real-time imaging with echocardiography20,21 or magnetic resonance imaging,22 and intracardiac probes that can provide detailed in vivo quantitative geometric relationships during the cardiac cycle.23 These recent imaging studies, referenced throughout this review, have advanced the understanding of the pathophysiology of mitral disease considerably.

Functional Anatomy and Classification of MR

The unique design of the mitral valve complex revealed by these studies highlights that its function must be considered in the context of its numerous component parts.24 The “functional anatomy” of the mitral valve includes the left ventricular myocardium, subvalvular apparatus (including papillary muscles and chordae tendineae), mitral annulus, mitral valve leaflets, and the left atrium.25,26 The pioneering cardiac surgeon Alain Carpentier, MD, PhD, developed a functional classification to reflect the underlying pathological changes that contributed to MR27 (Figure 1). As described in this classification, type I MR is characterized as normal leaflet motion but with annular dilatation or leaflet perforation; type II lesions are related to leaflet prolapse and may be caused by myxomatous disease, such as chord rupture or elongation, or by papillary muscle rupture or elongation; and type III lesions are caused by restricted leaflet motion. Type IIIA is typically caused by rheumatic valve disease with normal ventricular motion and subvalvular fibrosis and calcification; type IIIB is typically caused by ischemic or idiopathic cardiomyopathy with impaired ventricular function and dilation but a “normal” morphology to the leaflets, chords, and papillary muscles, frequently with restriction at the P3 segment. Type I MR may occur with billowing myxomatous leaflets but without elongated chordae and prolapse (type II), if extensive annular dilatation leads to inadequate leaflet coaptation.28 The posterior leaflet is divided into 3 segments, or scallops—P1 (lateral), P2 (middle), and P3 (medial)—and the A1, A2, and A3 segments of the anterior leaflet correspond to the opposing posterior leaflet segments (Figure 2).
Mitral Valve Complex and Annulus

In the process of repairing the mitral valve complex or approaching it percutaneously, one must consider the anatomy of the numerous adjacent structures to avoid injury and subsequent complications. Iatrogenic injury during surgical or percutaneous intervention (Figure 3) may occur to the aortic valve, circumflex coronary artery, coronary sinus, and conduction system. The mitral valve annulus has a "saddle" shape in 3 dimensions and is both muscular and fibrous\(^29\) (Figure 4). It integrates with the fibrous continuity of the mitral valve anterior leaflet and anterior annulus, which extend to the adjacent aortic valve annulus, thereby establishing fibrous continuity between the mitral valve and cusps of the aortic valve.\(^30\) The fibrous trigones, including the central fibrous body, border this aortomitral continuity (subaortic curtain) on each side. It had been accepted that the intertrigonal distance (the "fibrous skeleton" of the heart) is fixed and that its length does not change with mitral valve disease,\(^31\) a concept that will be examined later in this review. As the mitral annulus continues away from the fibrous skeleton, it becomes disproportionately muscular and is more prone to distortion and dilatation. Most mitral annular dysfunction occurs in the posterior and medial half of the valve. The annulus is dynamic, and its motion is coordinated by the cardiac cycle.

Valvular–Ventricular Interactions

Given its central position and network of valvular and subvalvular connections within the left ventricle, the mitral valve complex in healthy hearts "tethers" the fibrous skeleton of the heart to itself and, in so doing, plays an important role in maintaining its shape and function.\(^30,32\) The collagenous matrix elements within the chordae tendineae and papillary muscles are histologically continuous with the collagen network of the heart at 1 end and the mitral valve annulus and leaflets at the other.\(^15\) The concept of a functional "valvular–ventricular interaction" was first recognized in the 1960s by C. Walton Lillehei, MD, a pioneering cardiac surgeon from Minnesota, but took decades to be fully appreciated.\(^32–34\) As early as 1964, Lillehei et al\(^31\) recommended that the subvalvular apparatus be preserved during mitral valve surgery, to enhance ventricular functional recovery and maintain chamber size and shape (not the prevailing opinion at that time). In a clinical series, David et al\(^35\) confirmed this hypothesis by showing that chamber size increased with removal of mitral chordae in patients with chronic MR. Using large animal models, Stanford investigators performed a series of detailed studies confirming that removal of mitral chordae directly results in numerous detrimental effects on left ventricular shape, mechanics, and performance.\(^36–38\) After removal of the papillary muscles and their chordal attachments to the valve and to the valve annulus, the ventricle dilates, wall stress and afterload increase, and contractile function is compromised.\(^39\) Further experimental and clinical work indicates that preservation of chordae can facilitate the complete recovery of both global ventricular and individual myocyte function after chronic volume overload from MR, and late survival after mitral valve replacement can be enhanced with use of chordal-sparing techniques.\(^40\) A major tenet of mitral surgery today is that preservation of these relationships should be a consideration in all attempts to reconstruct the mitral valve complex.\(^41,42\)
Mitral Valve Pathologies

Although mitral valve repairs have been used for diverse pathophysiology, degenerative disease (myxomatous) and functional disease (chronic ischemic MR and dilated cardiomyopathy) are most frequently the motivation for repair of lesions.

Myxomatous Degeneration

Also known as mitral valve prolapse, “floppy valve,” or Barlow’s syndrome, the leaflets and chordae in myxomatous degeneration become thickened and redundant, which results in leaflet prolapse beyond the plane of the annulus and MR. The body of the leaflet may be billowing, but the valve will be competent if the chordae are normal length. When the chords are elongated, it causes prolapse beyond the opposing segment, and when the chords are ruptured (commonly called “flail”), MR is typically severe. Most often, this problem presents as prolapse of the P2 segment from ruptured chordae, and the echocardiogram shows an anteriorly directed jet. When A2 prolapses, the jet is directed posteriorly. The pathophysiology of myxomatous disease is poorly understood at the cellular and molecular level. The disorder appears to result from a defect, either congenital or acquired, in fibroelastic connective tissue homeostasis. Recent work suggests that valvular interstitial cells may mediate extracellular matrix remodeling in myxomatous degeneration by excessive secretion of catabolic enzymes. Caira and colleagues have proposed a novel molecular pathway that may contribute to the development of degenerative valve disease. The propensity for weakened chordae to rupture in degenerative disease may also reflect changes in the composition and regulation of matrix components.

“Functional” MR

Functional MR is caused by geometric ventricular remodeling without primary valve leaflet pathology. This condition is secondary to ventricular dilatation and is typically seen in idiopathic dilated cardiomyopathy and in postinfarction ventricular remodeling. The mechanisms of chronic ischemic MR are more complex than degenerative lesions. Typically, a posterior infarction with ventricular scar is present in the distribution of the circumflex or right coronary artery. This leads to localized regional wall-motion abnormalities associated with ventricular dilatation, a drop in ejection fraction, an increase in ventricular volumes, and remodeling to a globular heart (change in sphericity). Papillary muscle tethering restricts closure (Carpentier type IIIb), especially involving the medial commissure (P3 area), which creates an asymmetrical complex jet that is predominantly from the medial commissure but that also may originate from the lateral...
The principles of mitral valve repair have evolved. The classic “French correction” developed by Carpentier primarily involved quadrangular leaflet resection for those with prolapse, transposition of normal chords to other areas of prolapsing leaflet tissue if needed, and a remodeling annuloplasty with a complete ring prosthesis.\(^27\) The original “classic” Carpentier ring was flat and rigid.\(^52\) The mitral annulus is a dynamic, saddle-shaped structure with the maximum height of the saddle in the middle of the anterior part of the annulus and another rise along the posterior leaflet (P2; Figure 4). Accordingly, the next-generation “physio-ring” had selective flexibility and a slight 3D shape to conform better to the normal mitral annulus.\(^53\) Newer mitral rings have increasingly attempted to replicate this “normal” saddle shape, and “flexibility” has also been built into the design of various rings. Yet, despite a more “normal” valve physiology,\(^18,54,55\) superior long-term clinical results with flexible rings have not been demonstrated.\(^56–59\) The most recent annuloplasty rings are cause-specific, geometrically shaped to accommodate the underlying pathology, not to replicate the “normal” mitral annulus (Figure 5). A large variety of rings or bands are now available for mitral repair (the Table).

### Annuloplasty Rings and Bands

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Ischemic MR and Functional MR
Surgical undersizing of the mitral annulus in patients with cardiomyopathy will optimize leaflet coaptation and eliminate MR, a technique now known as a restrictive mitral annuloplasty and popularized by Bolling.60 Recurrent MR after initially successful mitral annuloplasty led to important observations.56,57 First, flexible annuloplasty bands can become distorted over time58; second, the intertrigone distance affects fewer than 10%.71–73 The incidence of SAM can be reduced with a sliding plasty, but this involves extensive leaflet resection and reconstruction. In addition, SAM may occur rarely despite sliding plasty due to a still-enlarged posterior leaflet, a long anterior leaflet, or too small a ring.

Myxomatous Disease and Systolic Anterior Motion
Carpentier refined his leaflet resection technique to include a sliding plasty to reduce the height of the posterior leaflet for patients with myxomatous disease and an excessively elongated posterior leaflet.69 This modification was designed to avoid systolic anterior motion (SAM), a complication that occurs when the coaptation point of the anterior and posterior leaflets is too close to the left ventricular septum70 (Figure 6), which creates left ventricular outflow tract obstruction. Intraoperative SAM may be managed with volume loading and by stopping inotropic drugs, but in some cases, it necessitates re-repair or replacement of the mitral valve with a prosthetic valve. SAM can occur in as many as 14% of patients with myxomatous disease after valve repair but more commonly affects fewer than 10%.71–73 The incidence of SAM can be reduced with a sliding plasty, but this involves extensive leaflet resection and reconstruction. In addition, SAM may occur rarely despite sliding plasty due to a still-enlarged posterior leaflet, a long anterior leaflet, or too small a ring.

Myxomatous disease is characterized by leaflet thickening and elongation, which may be generalized, involving all segments of both leaflets (characteristically called Barlow’s syndrome), or segmental, usually involving P2 but with normal height and thickness of P1 and P3 segments and anterior leaflet (fibroelastic deficiency).28,74,75 A spectrum between these 2 extremes is common. SAM can occur when the coaptation point is near the septum, because the residual posterior leaflet is tall or the annuloplasty ring chosen did not accommodate the enlarged leaflets from myxomatous disease.73 Complex leaflet reconstruction techniques, such as sliding plasty or reduction of anterior leaflet height,76 are technically more difficult than annuloplasty alone, and this is thought to be one of the important reasons why repair rates are low in this condition.7 This problem can be dealt with by the use of large-diameter rings77 or with a new ring (Myxo ETLogix, Edwards Lifesciences) designed specifically for myxomatous disease to accommodate larger leaflets and
move the coaptation point away from the septum (Figure 5). Because the new ring accommodates larger leaflets, the need for complex sliding plasty or other reconstruction is reduced, which hopefully will lead to increased rates of repair. In the earliest single-center report, the rate of sliding plasty was reduced from 38% to 0, but further confirmation is required.72

Edge-to-Edge Approximation (Alfieri Repair) and Artificial Chords

Two other surgical techniques have been added to the fundamental techniques of repair first described by Carpentier. Diseased or deficient chordae can now be replaced with artificial chordae using Gore-Tex (expanded polytetrafluoroethylene) either in lieu of chord transposition or without resection, thereby preserving the valve, including the elongated myxomatous leaflets.78 The second addition has been the reemergence of the edge-to-edge approximation of the leaflets, commonly called the Alfieri technique.79 This technique involves suturing together anterior and posterior leaflets at a single point midway between the circumferences of the leaflets (Figure 7). The Alfieri “edge-to-edge” repair can be used in diverse settings, including fixing the plane of coaptation at the level of the annulus to treat or avoid SAM.80,81 The Alfieri technique is typically used with other repair techniques and an annuloplasty, because results when used without an annuloplasty have been suboptimal, with recurrent MR and a high risk for reoperation (11% overall, 23% for those with annular calcification versus 5% without calcification, at a mean follow-up of 2.9 years), in Alfieri’s experience.81–83 These approaches are not without potential problems. Artificial chords may be left too long, which results in residual prolapse, or made too short, which leads to restriction of the leaflet and residual MR. The edge-to-edge repair can restrict the mitral orifice and potentially lead to mitral stenosis if thickening or stiffening of the leaflets is present. One goal of mitral repair is to preserve leaflet mobility, and the edge-to-edge repair may compromise that goal. The rate of recurrent 3 to 4+/ ischemic MR despite flexible band and edge-to-edge repair was unacceptably high (30%).81

Contemporary Results of Surgical Mitral Valve Repair

Successful mitral valve repair is achieved in \( \approx 80\% \) of all surgical cases of chronic MR.84 The importance of intraoperative transesophageal echocardiography cannot be over-
stated, and its use should be considered routine. The surgeon and echocardiographer discuss the severity of MR, the mechanism, the lesion, segmental valve pathology, subvalvular pathology and calcification, left ventricular size and function, left atrial size and thrombus, and other pathology, especially other valve lesions such as tricuspid regurgitation, aortic pathology such as atherosclerosis, a patent foramen ovale, and right ventricular dysfunction. After the repair has been completed and the patient has been weaned off cardiopulmonary bypass, the valve is reassessed for any residual MR (1+ or greater is cause for concern), SAM, and mitral gradient. Ventricular function is also assessed, and the heart is inspected for residual intracardiac air. Approximately 90% of degenerative lesions can be repaired successfully in expert centers by use of contemporary techniques.72,85 The advantages of mitral valve repair over replacement with a valve prosthesis are no longer debated, and mitral valve repair is the standard of care whenever it is feasible. Repair has been demonstrated to be superior in the setting of combined coronary bypass procedures, reoperations, double-valve procedures, and in elderly patients.86–89 However, no prospective randomized trial of repair versus replacement has been performed, and all reports contain some statistical shortcomings that may not be able to account for bias and heterogeneity. Some subgroups show no difference in survival,90 and propensity-adjusted studies have shown better survival with repair but no difference in quality of life.91 It is also not clear whether survival may be improved with chord-preserving mitral valve replacement rather than operations that remove all or part of the subvalvular apparatus. It is almost always possible to retain part of the subvalvular structures (especially to the posterior leaflet), but with mitral valve replacement for advanced rheumatic disease with subvalvular fibrosis and calcification, resection is frequently necessary to avoid interference with the prosthesis. Most patients maintain normal ventricular function with removal of part of the subvalvular apparatus. Given the excellent outcomes that are now obtained, the indications for mitral valve repair have been extended to a larger group of selected patients and to include repairing the valve before the onset of symptoms.6 Asymptomatic patients have demonstrated improved measures of exercise tolerance after repair.7 The Carpentier techniques offer outstanding long-term results for patients with type II (prolapse) MR.3

Reoperation rates certainly underestimate the amount of residual MR (persistent immediately after repair) or recurrent MR (initial successful repair, with MR redeveloping >30 days after surgery). Recent reports indicate that recurrent MR is very uncommon,92–94 but some cite a significant incidence of late 3 or 4+ MR.95–97 The early surgical literature did not investigate or report this discrepancy, but it is now becoming a routine part of mitral valve repair publications.98,99 It should be kept in mind that reports of late follow-up also reflect an era when the use of intraoperative echocardiography was not routine, so residual MR may have been undetected; some techniques have been largely abandoned (eg, chord shortening); and in general, repair techniques and rings were not as well developed. Recent reports of recurrent 3 to 4+ MR range from 1%72 to 4.8%,94 5%,92 9%,96 and 29%.95

Increasingly, new techniques are needed to address the growing population of patients with ischemic MR, particularly type IIIb disease, which can be particularly challenging. Conventional ring annuloplasty is prone to failure in these patients, with recurrent severe MR in 25% of patients as early as 1 year after surgery.56,57 Also, conventional wisdom dictated that mitral valve surgery for patients with left ventricular dysfunction carried excessive risk. This idea stemmed from an erroneous belief that a “pop-off mechanism” allowed the ventricle to decompress into the relatively low-pressure left atrium. Surgical repair of MR would presumably remove this adaptive pop-off mechanism, increasing the load on an already compromised ventricle, which would result in rapid deterioration and death. Recent results refute this long-held concept. The prospective randomized study of mitral valve repair as part of the Acorn “CorCap” cardiac support device trial (Acorn Cardiovascular, St Paul, Minn) in patients with dilated cardiomyopathy showed a very low operative mortality (1.6%), with reverse structural remodeling (reduced left ventricular volumes and sphericity), improved cardiac function, and enhanced quality of life.100

The benefits of remodeling the mitral annulus in patients with cardiomyopathy by use of cause-specific annuloplasty rings await the results of later follow-up, but the early results are encouraging.68 These results have also been observed in patients with undersized, rigid, complete remodeling rings.58 Studies using finite-element model analysis also support the concept of cause-specific annuloplasty rings.66

**Novel Mitral Valve Repair Approaches**

A variety of new percutaneous approaches to mitral valve disease are in early clinical use or undergoing preclinical investigation. Recent reviews of this broad area have been published.101,102 These concepts include mitral valve replacement (EndoValve Inc, Princeton, NJ), and with a variation of the transapical aortic valve replacement, transapical balloon-expandable valve replacement inside a failed bioprosthetic mitral valve replacement (“valve-in-valve”; personal communication, John G. Webb, MD, July 2007). However, the thrust of most current research and development is directed toward percutaneous approaches to mitral valve repair.

**Coronary Sinus and Annular Approaches**

There has been a great deal of interest in placing devices in the coronary sinus to push against the posterior portion of the mitral annulus and ideally improve coaptation of the posterior and anterior mitral valve leaflets.11–13 Some of these devices are now under clinical investigation.103–105 Considering the 1-year failure of conventional annuloplasty when sewn directly on the annulus with a variety of ring types and the complexity of the ischemic MR jet, achieving late success with this approach will be challenging and assumes that the patient has coronary anatomy that will allow the operator to place the device. Although success in animals has been obtained, human trials have presented more difficulties. Anatomic considerations may account for these problems, because often the coronary sinus does not lie directly adjacent to the posterior mitral valve annulus.106 The coronary sinus is an atrial structure and is not in the same plane as the mitral
valve annulus. In addition, the circumflex coronary artery or its numerous branches may lie between the mitral annulus and the coronary sinus (CS) and be vulnerable to compression, which limits the practicality of the coronary sinus approach for some patients. Reproduced from Choure et al108 with permission of the publisher. Copyright © 2006, the American College of Cardiology.

Figure 8. The relationship of the coronary sinus and the mitral annulus is variable, and in 64% of patients, the circumflex coronary artery (LCX) may travel between the coronary sinus (CS) and the mitral annulus (MA) and be vulnerable to compression, which limits the practicality of the coronary sinus approach for some patients. Reproduced from Choure et al108 with permission of the publisher. Copyright © 2006, the American College of Cardiology.

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Subvalvular Approaches

New concepts in ischemic mitral pathophysiology have resulted in the development of novel surgical approaches to treat complex ischemic mitral valve disease. Some procedures have focused on the subvalvular apparatus to enhance repair. Subannular procedures can either approximate the papillary muscles (papillary muscle sling),109 pull the papillary muscles toward the annulus to release leaflet tethering,110 or cut secondary chords to reduce tethering of the leaflets.111 These novel techniques have all been used with some success and are expertly reviewed by Levine and Schwammenthal112; however, the need for these techniques is uncommon, because the majority of patients with MR undergoing coronary bypass are treated with simple annuloplasty rings.112 Therapies that improve left ventricular systolic function and reduce left ventricular volume, such as β-adrenergic blockade or cardiac resynchronization therapy,113–115 have the potential to reduce the severity of functional MR during the course of reverse remodeling. Another approach to treating ischemic MR involves cell transplantation to promote reverse remodeling and stabilize the infarcted ventricle. Messas and colleagues116 determined that this approach alone could reduce MR in a chronic sheep model of ischemic MR. Recurrent MR after ring annuloplasty is associated with progressive chamber dilatation.117 Cell transplantation is well documented to prevent left ventricular dilation and restore systolic function in experimental models of ischemic cardiomyopathy.

Coapsys and i-Coapsys

The concept of moving the ventricle, rather than the annulus, to increase leaflet coaptation and eliminate functional MR led to the development of the Coapsys device (Myocor Inc, Minneapolis, Minn). This device employs a transventricular splint with pads on the outer surface of the left ventricle (Figure 9). In an open chest, this can be placed without cardiopulmonary bypass under direct echocardiographic guidance. Pads attached to each end of the splint are tightened gently to pull the ventricle into the region of the papillary muscles and also to move the posterior leaflet to better coapt with the anterior leaflet. The i-Coapsys device performs the same role but can be delivered in a minimally invasive procedure with fluoroscopic guidance. Clinical studies for the i-Coapsys will begin soon. Initial studies with the open-chest Coapsys system showed encouraging results, and a prospec-
Figure 9. The Coapsys device was designed to perform echocardiography-guided off-pump reduction or elimination of MR. The device consists of transventricular splints with an anterior pad on the right ventricular side of the septum and 2 posterior pads. One anterior pad is at the level of the mitral valve annulus, and when tightened under direct echocardiographic guidance, it can be seen to shorten the septal lateral dimension and increase coaptation of the anterior and posterior leaflet, thereby eliminating MR. The posterior inferior pad moves the midventricular portion of the heart (where the posterior papillary muscles arise), because tethering of the papillary muscles is the underlying cause of ischemic MR in these patients. RV indicates right ventricle; LV, left ventricle.

A balloon inflation device to displace the posterior wall is a similar concept that has not yet been tested in humans. A prospective randomized trial is under way in the United States. A balloon inflation device to displace the posterior wall is a similar concept that has not yet been tested in humans. A prospective randomized trial is under way in the United States.1,18,19

Summary

Mitral valve repair has matured and moved beyond the first generation of techniques and devices. We have a better understanding of the pathophysiology and limitations of prior approaches. New techniques and rings have been designed to increase effectiveness and durability of mitral valve repair, and it is hoped that these advances will translate into more widespread adoption of these techniques by surgeons. Percutaneous approaches to mitral valve repair are in their infancy, much as mitral valve repair itself was in the 1970s. An appreciation of the lessons learned from surgical mitral valve repair will aid in the development of novel percutaneous repair approaches that are safer, effective, and durable.

Disclosures

Dr McCarthy is the inventor of the Myxo ETLogix MV Ring and co-inventor of the Carpentier-Edwards-Adams IMR ETLogix ring and receives royalties for these products; he is also a consultant to Edwards Lifesciences (Irvine, Calif). Dr Bonow is a consultant to Edwards Lifesciences. Dr Fedak reports no conflicts.

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