A successful surgical approach to mitral regurgitation (MR) was first reported as early as 1951 by Bailey et al. (1). Since that time, surgical and percutaneous interventions to treat MR have evolved tremendously. At present, percutaneous means to repair the mitral valve (MV) or even replacing the MV appears to be on the horizon and promises to dramatically alter the treatment and selection of patients with MR. The purpose of this review is to summarize current surgical practice in treating MR, and to suggest where treatment for MR might be heading in the near future.

A Brief History

Bailey et al. (1) first approached MR through a left thoracotomy, and the mitral annulus was narrowed by external constriction of the base of the heart in an approach not unlike recent attempts to perform mitral annuloplasty through the coronary sinus. Lillehei et al. (2) performed the first direct suture annuloplasty of the MV in 1957 using cardiopulmonary bypass (CPB), and Starr and Edwards (3) first replaced the mitral valve using a commercially successful device in 1960. Today, surgery for MR is performed in 40,000 patients each year in the United States. One should be aware that, in this age of rapidly advancing percutaneous technology that is used both by surgeons and nonsurgical interventionists, the term “surgical” could, in fact, be considered an anachronism.

Anatomic Approaches to the Mitral Valve

The MV sits between the left atrium and the left ventricle, and can therefore be approached from either of those 2 chambers. At present, nearly all surgical access to the MV is through the left atrium. Rarely, the MV is approached through the left ventricle or the aortic root.

The left ventricular apex has previously been used to perform closed mitral commissurotomy. More recently, a transapical approach has been used to replace the MV using a percutaneous, stented aortic valve device in a patient with failed biological mitral prosthesis (4). Mitral chordae have also been replaced through a transapical approach (5). A transventricular approach to MV repair has been described in patients having left ventriculotomy performed for left ventricular aneurysm (6,7). The transventricular approach at the time of ventricular aneurysm repair is best suited for simple replacement or commissural annuloplasty.

Surgical Incisions to Access the Mitral Valve

To access the anatomic approaches to MR listed above, several skin incisions have been used, including sternotomy, thoracotomy, or percutaneous access. With wide use of CPB in the 1960s, median sternotomy replaced right thoracotomy as the primary surgical approach to treat MR due to reliability, speed, and excellent access to most of the heart. The skin incision for full sternotomy can be made as small as 8 cm and can be a cosmetic inframammary incision in women. Disadvantages to median sternotomy include blood loss, slow sternal healing, potential for sternal nonunion, and morbidity and mortality from deep sternal infection, which may affect 1% to 2% of cases.
Because of patient demand, marketing forces, and improved technology, the percentage of MV operations done with minimally invasive incisions other than sternotomy have steadily increased to 20% of all mitral operations in 2008 (8). Although large, controlled studies are lacking, minimally invasive approaches to the MV have been associated with faster recovery, less blood loss, and less infection (9). Disadvantages can include increased operative difficulty, increased procedure and pump times, limited access to the rest of the heart, potentially more equipment costs, and possibly more stroke due to greater use of femoral arterial cannulation for CPB (8,10).

Partial superior sternotomy has been the most popular minimally invasive approach to the MV since the work of Gillinov and Cosgrove (11). Before median sternotomy, mitral operation for regurgitation was performed through right thoracotomy by Lillehei et al. in 1956 (2). Many series now describe smaller right thoracotomies termed “mini” thoracotomy or “port access” (12,13), with an incision length somewhere between full thoracotomy (20 cm) and an endoscopic port (0.5 cm to 1.5 cm).

Transapical access to the MV can be obtained through a small left anterior thoracotomy and has been reported for valve-in-valve redo mitral replacement using the Sapien (Edwards Lifesciences, Irvine, California) percutaneous valve device (4). Inferior partial sternotomy, right parasternal incision, and left thoracotomy have all seen limited use due to worse exposure or more chest trauma than other approaches.

To patients and to most surgeons, the term “totally endoscopic” has generally implied no incision larger than the port for a 0.5 to 1.5 cm endoscope. However, in cardiac surgical circles, “totally endoscopic” has also been used to describe a right minithoracotomy in the 4 cm to 8 cm range with no rib spreading (14). To avoid confusion of terminology, Chitwood et al. (15) proposed a classification system whereby minimally invasive approaches are categorized, as in Table 1, on the basis of whether the surgeon uses direct vision, thoracoscopic visualization, or robotics for any portion of the surgery. Totally endoscopic MV surgery with no chest incision >1.5 cm generally requires robotic assistance and groin incision for femoral arterial and venous access.

Robotic assistance for MV surgery as currently practiced first became available in 2000 and has been championed by Mohr, Chitwood, and others (16). The current daVinci robot (Intuitive Surgical, Sunnyvale, California) is a remotely controlled servo where 1 or 2 operating surgeons sit at a console away from the patient and manipulate 2 to 4 servo-controlled arms. The robotic arms offer scaling where the instruments move smaller distances than the operator’s hands, tremor reduction, stereoscopic vision, and ×10 magnification. An additional bedside surgeon is needed to load the various robotic arms, pass sutures in and out of the wound, cut, tie, and perform manipulation not done by the robotic arms. The greatest merit to robotic assistance comes when surgical incisions are sufficiently small to prevent facile operating directly through the minithoracotomy (generally 4 cm or less) (Table 1). Disadvantages of a robotic approach include equipment cost and complexity, size and bulk of current technology, and difficulty with knot tying.

### Percutaneous Access to the Mitral Valve

The only well-documented percutaneous approach to MR in the United States today is the MitraClip (Abbott Laboratories, Abbott Park, Illinois), which remains in trial in the United States (17). This is a 13-mm clip that is applied to attach the anterior and posterior mitral leaflets together, similar to the surgical edge-to-edge surgical repair technique (see following discussion). The MitraClip is placed from the femoral vein and through the interatrial septum.

Initial results of the North American EVEREST (Efficacy of Vasopressin Antagonism in Heart Failure: Outcome Study With Tolvaptan) trial and the European experience show that MitraClip can reduce MR, reduce left ventricular volume, and improve quality of life and heart failure symptoms at 1 to 2 years (17). Limitations of the MitraClip include the requirement of a localized regurgitant jet, technical challenges of the transeptal approach, and lack of results beyond 2 to 3 years.

Concern has been voiced that MitraClip placement without ring annuloplasty may duplicate surgical reports of higher recurrent MR due to lack of an annuloplasty ring (11). Conversely, Maisano et al. (18) reported a series of patients with surgical edge-to-edge repair without ring with freedom from reoperation or >2+ MR of 80% at 12 years. Many of these patients had annular calcification, which may have effectively served as an annuloplasty.

An additional concern voiced is that MitraClip placement may increase the likelihood of needing subsequent replacement instead of repair. This concern is supported by data from the EVEREST trial and from Germany, where replacement rates were higher than expected in patients requiring surgery after MitraClip placement (19,20). Nonetheless, more data will be needed, as these are small series with short term follow-up and a relatively inexperienced
surgical community regarding repair of valves with a MitraClip in place (21). Most would interpret available data as supporting the MitraClip in patients who are high risk for surgery and have limited life expectancy (22).

**Mitral Repair Techniques**

**Annuloplasty.** Direct vision mitral annuloplasty was reported by Lillehei et al. in 1958 (2). Many studies have shown that mitral repairs employing some form of ring mitral annuloplasty have better durability than do ringless repairs (Fig. 1A) (23). This observation may result from the fact that nearly all valves with significant chronic MR have some degree of annular dilation. In addition, unlike normal hearts, failing hearts have permanent plasticity where the heart forever continues to deform favorably or unfavorably under changing loading conditions. That is not to say that all ringless repairs fail (24), only that recurrent MR is more likely if annuloplasty is not performed.

Mitral annuloplasty can be categorized as complete or partial annuloplasty, as suture annuloplasty versus ring annuloplasty, and as rigid versus flexible ring annuloplasty. Partial annuloplasty and suture annuloplasty may be useful in children because of the potential for the unsutured annulus to grow and avoid mitral stenosis. For myxomatous MVs with prolapse, both rigid and flexible rings have similarly good results. Flexible rings theoretically have the advantage of allowing the base of the heart to contract, whereas rigid rings are more resistant to central leakage in patients with left ventricular (LV) dilation. In patients with functional MR, the net advantages of the complete rigid ring exceed those of the flexible ring (25). One series of prolapse patients suggests that flexible rings may have less ring dehiscence than rigid rings (26). Rigid rings may give more predictable geometry after repair for lower volume surgeons. The relative role for different ring shapes is unclear, except that narrowing the septal-free wall diameter is important in functional regurgitation (27). Concern has been expressed that smaller under-sized (24 mm or 26 mm) mitral rings could cause mitral stenosis and/or LV diastolic dysfunction (28). However, most agree that a 4 to 6 mm Hg mean gradient across a 24 to 26 mm ring is of less physiologic importance than is recurrent MR. Large series suggest that both partial and complete rings can provide good results in myxomatous prolapse valves. Complete, rigid rings, again, are considered by most surgeons to have the best results in patients with functional MR (25).

**Leaflet resection.** In addition to the ring annuloplasty, Carpentier et al. (29) made the major contribution of suggesting quadrangular resection of redundant posterior leaflet segments (Fig. 1B). By undermining the remaining posterior leaflet segments, more than one-half of the posterior leaflet can be resected. This “sliding leaflet plasty” reduces the height (annulus to free edge) of the remaining posterior leaflet to <1.5 cm to prevent anterior leaflet systolic anterior motion. A small triangular resection may be used for smaller segments of the posterior leaflet. Although posterior leaflet resection has been shown to be very reproducible, concern has surfaced that, in some patients, resectional techniques can decrease coaptation between the remaining posterior and anterior leaflets with subsequent recurrent regurgitation due to further valve remodeling (26). Equilateral triangular resections of the anterior leaflet up to approximately 1 cm in length can be used to correct focal anterior leaflet pathology (29).

**Chordal replacement, shortening.** Ruptured, elongated, or shortened primary chords can be replaced without leaflet resection. Normal chords can be transferred from secondary chords on the same leaflet or from primary chords on the opposing posterior leaflet (Fig. 1C). Increasingly, surgeons have been replacing chords with polytetrafluoroethylene

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**Figure 1** Common Established Surgical Techniques Used to Correct Mitral Regurgitation

(A) Ring annuloplasty. (B) Quadrangular resection and sliding leaflet plasty. (C) Chordal transfer. (D) Cleft closure. (E) Mitral replacement. Figure illustration by Craig Skaggs.
suture (Fig. 2A) (30,31). Disadvantages of chordal replacement remain difficulty getting chordal length right and stable chordal attachment to the mitral leaflet and papillary muscle.

**Leaflet augmentation or patch.** Leaflet perforations have long been patched using fixed native or bovine pericardium. Recently, restricted posterior leaflets have been patch augmented with some early success (Fig. 2B) (32). Long-term results of leaflet patching are unclear in any situation.

**Cleft closure.** Large leaflet clefts can occur with congenital leaflet variants and are easily closed (Fig. 1D). Many regurgitant MVs of any etiology can have abnormally open clefts due to annular dilation. These also can be sutured closed to improve the repair.

**Edge-to-edge repair.** Alfieri et al. (33) described a technique first applied in 1992 in which leaflet malapposition was corrected by suturing the anterior leaflet to the posterior leaflet in 1 place (Fig. 2C). The name “edge-to-edge” is a bit of a misnomer because ideally 3 mm to 5 mm of each leaflet edge is opposed to the other leaflet to force an area with a coaptation height of at least 3 mm to 5 mm. The edge-to-edge repair also can prevent systolic anterior motion of the anterior leaflet with LV outflow tract obstruction by fixing the anterior leaflet to the posterior leaflet (34). The edge-to-edge technique is generally used in conjunction with annuloplasty, but annuloplasty may be omitted in patients with hypertrophic obstructive cardiomyopathy to minimize outflow tract obstruction (24). Edge-to-edge repair may not be advisable in patients with rheumatic or stiffened leaflets or in patients with ring size <30 mm to avoid significant mitral stenosis. Limited results up to 10 years have been published with edge-to-edge repairs (24).

**Ventricular repairs.** Functional MR results from LV dilation. As a result, many authors have attempted ventricular or papillary muscle based repairs for functional MR along with mitral annuloplasty. Posterior wall plication (Fig. 2E) (35) and papillary muscle approximation (Fig. 2D) (36) have both been reported to have good early results.

**Results of Mitral Repair**

Many factors can diminish the likelihood of mitral repair versus mitral replacement. Factors predicting replacement instead of repair include low surgeon/institution volume, anterior leaflet pathology or bileaflet pathology, rheumatic etiology, infectious etiology, functional/ischemic etiology, and secondary leaflet changes such as scarring and/or calcification (37). Although surgeons are under pressure to have high rates of MV repair, recurrent MR can often be worse than the consequences of initial mitral replacement. “Good” repairs are generally better than replacement, but replacement is generally better than “bad” repair with recurrent regurgitation.

Freedom from reoperation at 20 to 25 years has been 90% in several large series (38–42) (Fig. 3). Factors such as anterior leaflet pathology or bileaflet pathology, rheumatic etiology, infectious etiology, functional/ischemic etiology, secondary leaflet changes such as scarring and/or calcification, lack of ring annuloplasty, and low volume for the surgeon or institution tend to predict a higher likelihood of reoperation (43).

Only recently have several large studies with a high degree of echocardiography follow-up reported residual/recurrent MR after mitral repair (26,40,42,44,45). The goal of surgical mitral repair has been to leave the operating room with no more than
mild residual MR by transesophageal echocardiography under anesthesia, as more than that has been associated with a higher rate of reoperation (46). At 10 years, MR has been reported as at least moderate in 15% to 30% of patients having myxomatous valve repaired and severe in 5% to 10% (Fig. 4)(26,40,42,44,45).

For patients with functional or ischemic etiology, moderate or more regurgitation has been reported in 20% to 30% of patients at 1 to 5 years (44), prompting some surgeons to consider mitral replacement or not addressing the MV in some patients (47). Others have criticized these studies because of their use of full-sized, partial, flexible rings, which many now think allow more unfavorable annular remodeling (48). Use of complete, rigid, and under-sized or reduced septal-free wall diameter rings is now favored for repair of ischemic or functional MR by many authors (48).

**Mitral Replacement**

Mitral replacement had long been the standard surgical treatment for MR (Fig. 1E), but mitral repair is now favored over replacement in most patients. Advantages of mitral repair versus replacement include avoidance of mandatory anticoagulation, potentially better durability than bioprostheses, less impairment of LV function, less risk of LV posterior wall rupture (ventricular-annular disruption), and lower early and late mortality (49). Some of the advantages of mitral repair over replacement come from the fact that previous mitral replacements tended to resect all of the native MV chords. However, many studies have now shown that mitral replacement with chordal preservation nearly eliminates the risk of ventricular-annular disruption and minimizes impairment of LV function (50). Indeed, to date, no definitive data exist to say that mitral repair has an advantage over chordal sparing mitral replacement, beyond the inherent issues of anticoagulation versus limited biological durability.

Mitral replacement does have some inherent advantages over repair. The elimination of MR is more certain with replacement, especially when the quality of repair is in question. Elderly patients with limited life expectancy may have little issue with anticoagulation therapy or limited durability using modern bioprostheses. Mechanical mitral replacement with anterior leaflet resection was described by Krajcer et al. (51) for hypertrophic obstructive cardiomyopathy with effective elimination of both MR and LV outflow tract obstruction. Some researchers believe that MV replacement may be a more effective therapy than mitral repair for patients with ischemic MR, especially if the mitral leaflet is restricted >1 cm below the plane of the mitral annulus (52).

The selection of biological versus mechanical prostheses for mitral replacement remains controversial. The last decade has seen a significant shift toward biological mitral prostheses due to an aging population, hope that reoperation can be less invasive or percutaneous, patient dislike of anticoagulation therapy, and belief that modern bioprostheses are more durable. Unfortunately, replacement of a failed biological prosthesis remains a morbid procedure, and a significant percentage of patients having biological mitral replacement will require anticoagulation therapy for atrial fibrillation during their subsequent course. Data actually suggest that the durability of current bioprostheses in the mitral position remain limited, especially in patients <60 years of age (Fig. 5) (53,54). Transapical replacement of failed biological mitral prostheses has been reported using percutaneous bioprostheses designed for the aortic position (4). Several new anticoagulants are on the horizon with the potential
to eliminate frequent testing and/or minimize bleeding complications with mechanical prostheses.

**Indications for Mitral Repair or Replacement**

As the results of surgery for MR have improved, the threshold for operating on MR has been lowered. Today, the mortality for isolated mitral repair is 1% to 2%, and the mortality for isolated mitral replacement is 6% (37). Published guidelines for management of valvular heart disease (55) are data driven and useful, but guidelines need to be adjusted for each individual patient. For patients with a 90% likelihood of obtaining a mitral repair, surgery today is seldom performed as an isolated procedure for less than severe MR because of the low mortality and the low rate of symptoms for moderate MR.

The indications for operation on ischemic or functional MR remain more controversial than those for degenerative disease. Despite data that functional regurgitation is associated with impaired survival, nonrandomized studies have suggested that survival is not improved by mitral repair for functional regurgitation when the ejection fraction is <30% (56). Most believe that heart failure symptoms can be improved after repair of functional regurgitation in patients with appropriate LV functional reserve (56).

**Post-Operative Management**

Two controversies in the early management of surgical patients are management of anticoagulation therapy and atrial fibrillation prophylaxis. Unless significant atrial fibrillation occurs in the postoperative period, most mitral repair or biological replacement patients can be managed with aspirin alone. Short-term anticoagulation therapy with warfarin for 3 months is not uncommon, as mitral patients have a 30% to 70% incidence of new atrial fibrillation after mitral surgery. Most large centers would use an antiarrhythmic like amiodarone in patients for 1 to 3 months to minimize postoperative atrial fibrillation and subsequent anticoagulation. Concurrent Maze procedure may have a role in minimizing but not eliminating atrial fibrillation in patients at high risk for atrial fibrillation.

**The Future**

The next 10 years will see many changes in the surgical approach to MR. Certainly, the very early experience with percutaneous MV repair will grow. The percutaneous MitraClip is a perfect example of how familiarity with long-standing surgical approaches like edge-to-edge repair can lead to new approaches for the interventional cardiologist. Noninterventional cardiologists need to be familiar with the changing options and indications for evolving surgical approaches to MR. Open surgical approaches to MR will become less morbid as facilitating technology develops and allows smaller incisions and/or elimination of CPB. Stand-alone percutaneous therapies for MR will always have the potential to be applied through open surgical approaches also, thus blurring the distinction between the interventional cardiologist and the cardiovascular surgeon. Collaboration between the interventional cardiologist with percutaneous skills and the cardiovascular surgeon with open skills will create hybrid approaches to MR that would not be possible by purely percutaneous or open procedures alone (57).

**Perspective**

Already today and increasingly in the future, the surgical and interventional approaches to MR will be composed of a spectrum of approaches, spanning from maximally invasive to percutaneous. Patient selection for the appropriate approach will, therefore, become increasingly important once we have data regarding the outcomes of each approach in different patient subsets. To further complicate decision making, procedure invasiveness/morbidity may often be inversely related to procedure effectiveness. Thus, we may tend to favor less invasive but less effective approaches to treating MR in patients who are at higher risk and with limited life expectancy. Younger- and lower-risk patients may be more appropriate for more effective therapies while better tolerating any morbidity or risk. As less invasive approaches to MR become more available, some of the large pool of patients receiving little or no therapy for MR may become more likely to refer themselves, or to be referred, for some form of anatomic rather than medical treatment of their MR. Thus, technology continues to be a dominant driver of medical care for MR, just like most other diseases.

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