Degenerative Mitral Valve Repair Simplified: An Evolution to Universal Artificial Cordal Repair

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Background. **Resectional and artificial cordal repair techniques are effective strategies for degenerative mitral valve (MV) repair. However, resectional repair requires a tailored approach using various techniques, whereas cordal repair offers a simpler, easily reproducible repair. The approach described in this study approach has evolved from resectional to cordal over time, and outcomes are compared between the eras.**

Methods. **Clinical and echocardiographic outcomes of all patients undergoing MV repair for degenerative mitral regurgitation (MR) from January 2004 to September 2017 were reviewed. Patients were stratified by era: from January 2004 to June 2011 (era 1; n = 405), resectional techniques were used in 62% and artificial cordal techniques were used in 38%. From July 2011 to September 2017 (era 2; n = 438), artificial cordal repair was used in 98% of patients. The primary outcome was repair failure, defined as greater than moderate MR or MV reoperation.**

Results. **Of 847 patients with degenerative MR, successful repair was achieved in 843 patients (99.5% repair rate). Leaflet prolapse was posterior in 66%, anterior in 8%, and bileaflet in 26%. Cardiopulmonary bypass time and cross-clamp times were shorter in era 2 (CPB: 109 [IQR, 92–128] minutes vs 97 [IQR, 76–121] minutes; $P < .001$; cross-clamp: 88 [IQR, 73–106] minutes vs. 79 [IQR, 61–99] minutes; $P < .001$). Predismissal echocardiography demonstrated no MR or trace MR in 95%, mild MR in 4.7%, and moderate MR in 0.3% of patients. Operative mortality was similar in the eras (0.5% vs 0.5%; $P > .999$). The rates of 5-year freedom from repair failure (95.1% vs 95.5%; $P = .707$), stroke (96.8% vs 95.3%; $P = .538$), and endocarditis (99.3% vs 99.7%; $P = .604$) were similar between the eras.**

Conclusions. **Artificial cordal repair for all patients with degenerative MR simplifies MV repair and yields equivalent, excellent outcomes compared with a tailored resectional approach.**

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Degenerative mitral valve (MV) disease is the most common form of heart valve disease in North America.[1,2] MV repair has been established as superior to MV replacement, and societal guidelines recommend MV repair for patients with severe primary mitral regurgitation (MR).[3]

Procedures to repair the MV using resectional techniques were initially established by Carpentier.[4] These techniques include at minimum insertion of an annuloplasty ring and resection of the prolapsing segment of the mitral leaflet, but they frequently require additional maneuvers including sliding plasty, annular plication, chordal transfer, anterior leaflet resection, commissuroplasty, and others.[5-8] Although excellent long-term results have been reported using these techniques, resectional repair requires a complex patient-tailored approach that can be difficult to reproduce and teach. Zussa and colleagues[9] first reported the experimental and clinical use of expanded polytetrafluorethylene (ePTFE) cords to achieve MV repair by replacing ruptured or elongated native chordae tendineae. This artificial cordal repair MV repair strategy has excellent documented midterm and long-term outcomes.[10-12]

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At our institution, we predominantly used a resectional strategy in an earlier era of MV repair with an evolution toward artificial cordal repair over time. We learned that the artificial cordal repair strategy was simple, effective, easy to reproduce, and easy to teach to trainees. As a result, the resectional approach was abandoned, and artificial cordal repair techniques were performed nearly universally since July 2011. We hypothesized that a universal artificial cordal repair approach to MV repair would result in excellent outcomes similar to those seen with a tailored approach using both resectional and artificial cordal repair techniques.

Patients and Methods

Study Population

With Institutional Review Board approval, a retrospective review of the local Society of Thoracic Surgeons Adult Cardiac Surgery Database for all consecutive primary MV repairs by a single surgeon for degenerative MR from January 1, 2004 to September 1, 2017 was performed (N = 843) (Figure 1).

A manual review of patient charts was then undertaken to confirm the diagnosis and obtain preoperative, perioperative, and postoperative variables and outcomes. Clinical or echocardiographic follow-up was available in 89% of patients (751 of 843 patients), with clinical follow-up available in 85% (718 of 843) and echocardiographic follow-up available in 79% (663 of 843). Mean clinical follow-up time was 4.8 ± 3.8 years, and mean echocardiographic follow-up time was 4.4 ± 3.6 years.

For analysis, patients were stratified into 2 eras. From January 2004 to June 2011 (era 1), resectional techniques were used in 62% (252 of 405) of patients, and artificial cordal repair was used in 38% (153 of 405). From July 2011 to September 2017 (era 2), artificial cordal repair techniques were used in 98% (431 of 438) of patients (Figure 2).

Operative Technique and Postoperative Management

Procedures were performed through a median sternotomy with a limited skin incision or through a small right thoracotomy (less invasive).[13] The use of the less invasive operative approach decreased over time because the operating surgeon found it difficult to teach trainees using a right thoracotomy approach and did not observe benefits in terms of postoperative pain reduction (Supplemental Figure 1).

For procedures performed through median sternotomy, bicaval venous and central aortic cannulation was used with direct aortic clamping, as well as both antegrade and retrograde cardioplegia. For procedures performed through a right thoracotomy, femoral venous and arterial cannulation was used. The aorta was directly clamped, and only antegrade cardioplegia was used.

Resectional repairs were performed with a triangular resection, quadrangular resection, or leaflet imbrication in conjunction with adjunct techniques (sliding plasty, annular plication, commissural closure, cleft closure, or adjunctive imbrication). Artificial cordal repair was performed by placing ePTFE sutures from the papillary muscle to the free edge of the prolapsed segment or segments of the MV. ePTFE cordal pairs are spaced 3 to 4 mm apart on the free edge of the prolapsed segment or segments. Our practice evolved from the use of flexible partial annuloplasty bands to the universal use of nonplanar semirigid complete annuloplasty rings over time.

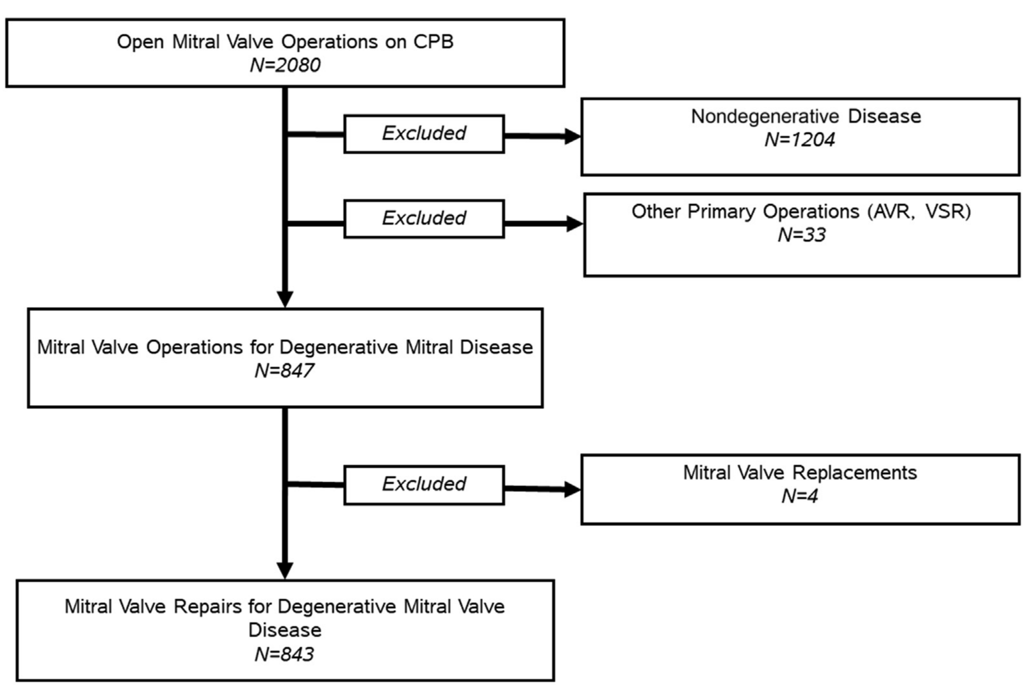


Figure 1. Consort diagram describing mitral valve operations performed by a single surgeon between January 1, 2004 and September 1, 2017. (AVR, aortic valve replacement; CPB, cardiopulmonary bypass; VSR, valve-sparing root.)

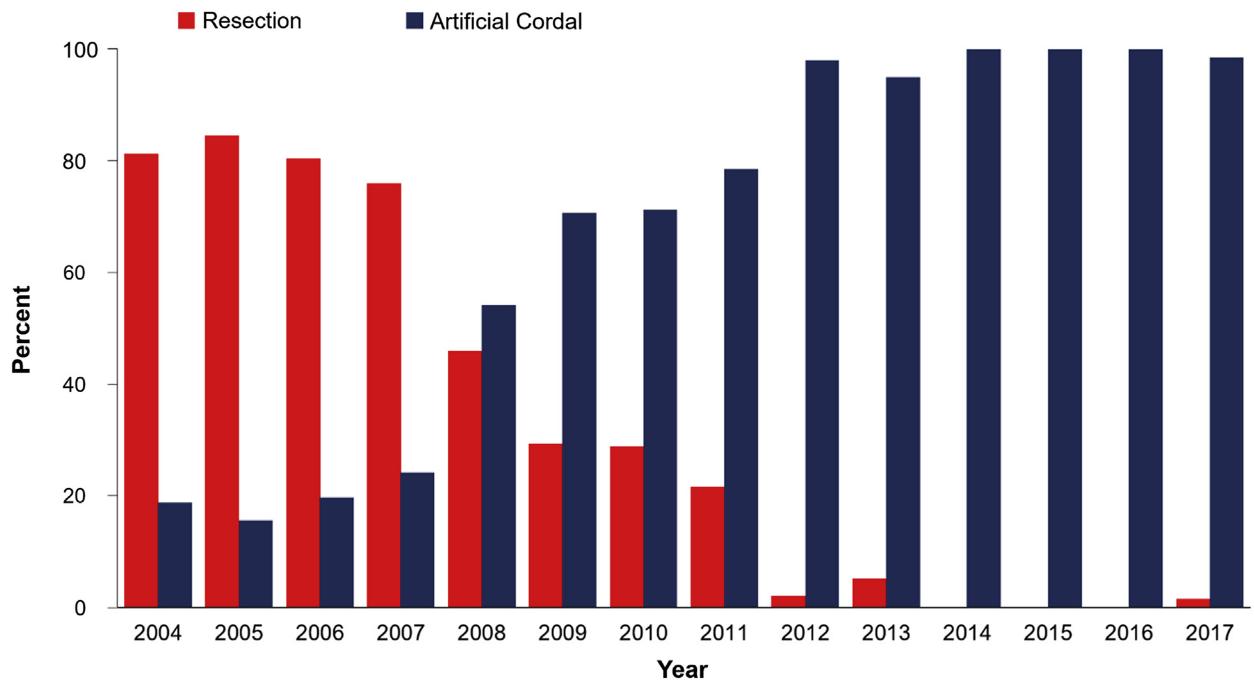


Figure 2. The use of resectional and artificial cordal repair techniques for mitral valve repair over time.

All patients undergoing a CryoMaze procedure were discharged on anticoagulation.[14] Patients who had isolated MV repair were discharged on aspirin alone.

Follow-up Echocardiography

MR was assessed intraoperatively using transesophageal echocardiography in all patients. Predischarge echocardiography was performed in 828 of 843 (98%) patients, with semiquantitative assessment of MR grade, along with assessment of MV gradient. MR was classified as none or trace, mild, moderate, and severe, according to the American Society of Echocardiography guidelines.[15]

Outcomes

The primary outcome of the study was freedom from repair failure, defined as MV reoperation or greater than moderate MR on late follow-up. Secondary short-term outcomes included operative mortality, in-hospital stroke, predischarge MR, predischarge mean gradient, and intraoperative systolic anterior motion (SAM). Secondary late outcomes included 5-year freedom from mortality, endocarditis, and stroke, as well as change in ejection fraction, change in systolic pulmonary artery pressures, New York Heart Association functional class, and mean gradient.

Statistical Analysis

Data were analyzed using SAS Statistical Software version 9.3 (SAS Institute, Cary, NC). Continuous variables are presented as mean ± SD for normally distributed variables or median with interquartile range (IQR) for nonnormally distributed variables and were compared with a Student *t* test or a Mann-Whitney *U* test, as appropriate. Categorical variables are presented as frequency (%) and compared using the χ^2 or Fisher exact test. Changes in ejection fraction and systolic pulmonary artery pressure from before surgery to follow-up echocardiography by era group were evaluated using repeated measures analysis of variance. Freedom from repair failure, stroke, and endocarditis was calculated using the Kaplan-Meier method from the time of operation to repair failure or last known follow-up. Differences were compared using the log-rank test. Sensitivity analyses examined freedom from repair failure, stroke, and endocarditis by era with death as a competing risk, but these analyses found no meaningful differences from the Kaplan-Meier survival analyses. To assess risk factors for repair failure, univariate Cox proportional hazards regression analyses were performed. Multivariable analyses of 5-year outcomes were then conducted by Cox proportional hazards regression analyses, adjusting for age, sex, and era.

Results

General Patient Characteristics

The mean age was 61 ± 13 years, 65% of patients were male, and 87% were white. Comorbid conditions included hypertension (55%), dyslipidemia (48%), and atrial fibrillation (28%). Left ventricular ejection fraction was reduced (<60%) in 35% of patients, and systolic pulmonary artery pressure was elevated (>40 mm Hg) in 31% (Table 1).

Degenerative disease affected the posterior leaflet in 66%, the anterior leaflet in 8%, and both leaflets in 26% of patients (Supplemental Table 1). Resectional techniques

Table 1. Patient Characteristics

Characteristics	Overall N = 843	Era 1 n = 405	Era 2 n = 438	*P* Value
Demographics				
Age (y)	61 ± 12	59 ± 13	62 ± 12	<.001
Male	549 (65)	278 (69)	271 (62)	.039
Race				.504
African-American	75 (9)	35 (9)	40 (9)	
White	733 (87)	359 (89)	374 (86)	
Other	35 (4)	10 (2)	19 (5)	
Comorbid conditions				
Atrial fibrillation	236 (28)	116 (28)	120 (28)	.718
Diabetes	66 (8)	27 (7)	39 (9)	.292
Dyslipidemia	399 (47)	205 (51)	194 (45)	.137
Hypertension	459 (54)	234 (58)	225 (52)	.133
LVEF				<.001
Normal (≥60%)	515 (65)	219 (57)	296 (72)	
Reduced (<60%)	281 (35)	167 (43)	114 (28)	
Baseline EF (%)	59 ± 8.3	57.7 ± 9.7	59.8 ± 6.8	<.001
sPAP	(594/843)	(334/405)	(260/438)	.003
Normal (<40 mm Hg)	412 (69)	215 (64)	197 (76)	
Elevated (>40 mm Hg)	182 (31)	119 (36)	63 (24)	
Previous cardiac surgery	34 (4)	9 (2)	25 (6)	.007
Previous MV surgery	12 (2)	0 (0)	12 (3)	<.001
Previous sternotomy	27 (3)	7 (2)	20 (5)	.019
NYHA functional class III or IV	336 (40)	165 (41)	171 (39)	.692
STS PROM (%)	(566/843)	(275/405)	(290/438)	.818
	0.51 (0.31-1.00)	0.44 (0.29-1.08)	0.57 (0.32-0.99)	

Data presented as frequency (%), mean ± SD, or median (interquartile range).

EF, ejection fraction; LVEF, left ventricular ejection fraction; MV, mitral valve; NYHA, New York Heart Association; sPAP, systolic pulmonary artery pressure; STS PROM, The Society of Thoracic Surgeons predicted risk of mortality.

were used in 28% of cases overall. There was a marked progression away from resectional techniques toward artificial cordal repair techniques over time, and artificial cordal repair techniques predominated after 2007. A less invasive operative approach was used in 26% of cases, but it also decreased over time, with more than 40% of operations performed using a less invasive approach between 2004 and 2009 but substantially fewer thereafter. Concomitant procedures were performed in 37% of cases.

Patient Characteristics by Era

Patients in era 2 were older (62 ± 12 years vs 59 ± 13 years; $P < .001$) and less likely to be male (62% vs 69%; $P = .039$). Patients in era 2 were more likely to have a normal left ventricular ejection fraction (72% vs 57%; $P < .001$) and normal systolic pulmonary artery pressures (76% vs 64%; $P = .003$).

Operative Characteristics

Of 847 patients with degenerative MV disease, MV repair was performed in 843 (99.5%). During era 1, 62% of patients underwent MV repair with resectional techniques, and 38% had artificial cordal repair techniques. Resection was performed with a triangular resection in 56%, a quadrangular resection in 25%, and leaflet imbrication in 19% of patients. A sliding plasty was performed in 19% of resections. During era 2, 98% of patients underwent artificial cordal repair techniques, and 2% underwent resection ($P < .001$). Artificial cordal repair was performed with a median of 4 (IQR, 3–4) pairs of ePTFE cords (Table 2). An annuloplasty ring was placed in 99% of patients (831 of 843). Mean ring size was 31 ± 3 in era 1 and 32 ± 3 in era 2 ($P = .099$). A partial flexible ring was used in 51% of patients, and a complete nonplanar semirigid ring was used in 47% of patients during era 1. In contrast, in era 2, a complete nonplanar semirigid ring was used in 99% of patients ($P < .001$).

Compared with era 1, median cardiopulmonary bypass time and myocardial ischemia time were shorter in era 2 (cardiopulmonary bypass, 109 [IQR, 92–128] minutes vs 97 [IQR, 76–121] minutes; $P < .001$; myocardial ischemia, 88 [IQR, 73–106] minutes vs 79 [IQR, 61–99] minutes; $P < .001$). These differences remained significant for isolated MV repairs without concomitant procedures and when comparing only those patients undergoing full sternotomy. Despite the nearly universal use of artificial cordal repair in era 2, the incidence of intraoperative SAM requiring medical or surgical intervention was similar in era 1 and era 2 (3% vs 4%; $P = .488$). There was also no significant difference in the incidence of intraoperative SAM when comparing resectional MV repair with artificial cordal repair approaches (3% vs 4%; $P = .310$).

Perioperative Outcomes

At discharge, 95% (782 of 843) of patients had no MR or trace MR, 4.8% (39 of 843) had mild MR, and 0.1% (1 of 843) had moderate MR. No patients were discharged with

Table 2. Operative Details

Details	Overall N = 843	Era 1 n = 405	Era 2 n = 438	*P* Value
Less invasive	223 (26)	193 (48)	30 (7)	<.001
Concomitant procedures	308 (37)	146 (36)	163 (37)	.778
CryoMaze	198 (24)	100 (25)	98 (24)	.704
CABG	102 (12)	57 (14)	45 (10)	.096
TV repair	83 (10)	25 (6)	58 (14)	<.001
CPB (min)	105 (87-126)	109 (92-128)	97 (76-121)	<.001
Isolated MV CPB (min)	94 (76-113)	100.5 (88-118)	83 (70-101)	<.001
Myocardial ischemia (min)	82 (66-103)	88 (73-106)	79 (61-99)	<.001
Isolated MV myocardial ischemia (min)	73 (60-88)	79 (66-94)	65.5 (56-80)	<.001
Intraoperative SAM	31 (4)	13 (3)	18 (4)	.488
Required rearrest	11 (36)	4 (31)	7 (39)	.641
Artificial cordal repair	583 (69)	153 (38)	430 (98)	<.001
Number of cordal pairs	3 (1-4)	2 (0-3)	4 (3-4)	<.001
1	51 (6)	43 (10)	8 (2)	
2	115 (14)	84 (21)	31 (7)	
3	201 (24)	68 (17)	133 (30)	
4	183 (22)	26 (6)	157 (36)	
5	63 (7)	15 (4)	48 (11)	
6	32 (4)	9 (2)	23 (5)	
7	17 (2)	2 (0.5)	15 (3)	
8	7 (0.8)	2 (0.5)	5 (1)	
9	2 (0.2)	0 (0)	2 (0.5)	
Resection	260 (30)	252 (62)	8 (2)	<.001
Triangular resection	146 (17)	140 (56)	6 (75)	.281
Quadrangular resection	62 (7)	62 (25)	0 (0)	.107
Imbrication alone	50 (6)	49 (19)	1 (0.1)	<.001
Adjunctive techniques				
Imbrication	27 (3)	10 (2)	17 (4)	.328
Sliding plasty	49 (6)	48 (12)	1 (0.2)	<.001
Commissural closure, anterior	41 (5)	9.0 (2)	32 (7)	<.001
Commissural closure, posterior	162 (19)	88 (22)	74 (17)	.073
Cleft closure	256 (30)	123 (30)	133 (30)	.999
Annuloplasty components				<.001
Complete semirigid	641 (76)	208 (51)	433 (99)	
Partial flexible	189 (22)	189 (47)	0 (0)	
No ring	12 (2)	8 (2)	4 (1)	
Ring size				.032
24	1 (0.1)	1 (.3)	0 (0)	
26	44 (5)	28 (7)	16 (4)	
28	121 (15)	60 (15)	61 (14)	
30	230 (28)	101 (26)	129 (30)	
32	164 (20)	93 (24)	71 (16)	
34	132 (16)	52 (13)	80 (19)	
36	75 (9)	35 (9)	40 (9)	
38	43 (5)	20 (5)	23 (5)	
40	15 (2)	5 (1)	10 (2)	

Data presented as frequency (%), mean ± SD, or median (interquartile range).

CABG, coronary artery bypass graft; CPB, cardiopulmonary bypass; MV, mitral valve; SAM, systolic anterior motion; TV, tricuspid valve.

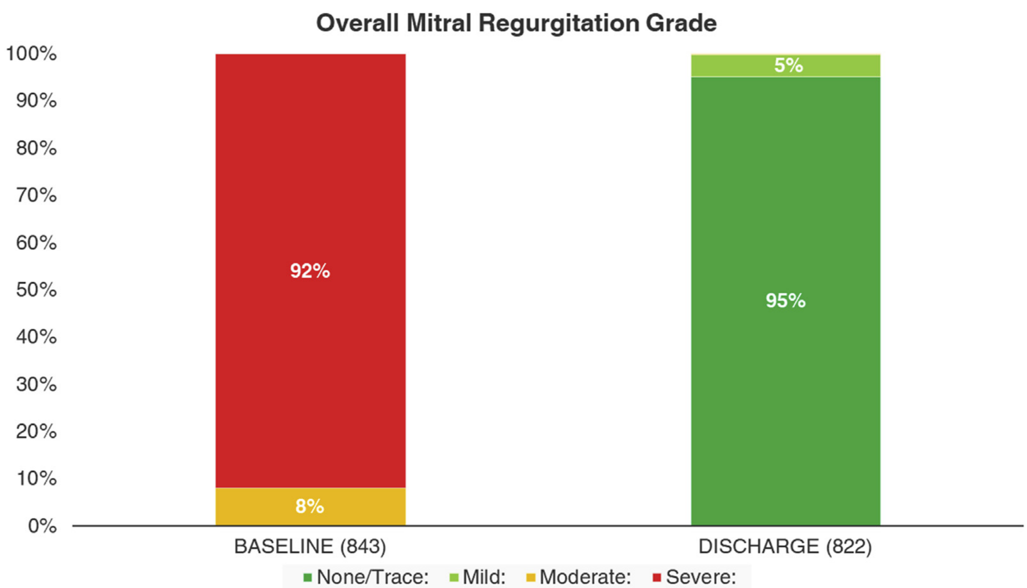


Figure 3. Preoperative, intraoperative, and early postoperative mitral regurgitation of the overall cohort of patients.

greater than moderate MR. Predischarge MR grades were similar between the 2 eras (Figure 3). Mean gradient at discharge was also similar between era 1 and era 2 (4 mm Hg vs 4 mm Hg; $P = .999$) (Table 3).

Five patients (0.6%) had a postoperative cerebrovascular accident. Two patients (0.2%) had a disabling stroke (modified Rankin score ≥ 2). The incidence of in-hospital postoperative cerebrovascular accident was similar between era 1 and era 2 (0.5% vs 0.7%; $P > .999$).

Operative mortality was 0.5% in both eras ($P > .999$). There were 4 in-hospital deaths, all secondary to multisystem organ failure.

Late Follow-up

At 5 years after operation, the freedom from endocarditis was 99.4%, and the freedom from stroke was 96.3% (Figure 4). These results were was similar between the 2 eras. Preoperative characteristics including atrial fibrillation (hazard ratio [HR], 0.66; 95% confidence interval, 0.15 to 2.87; $P = .582$) were not predictive of late stroke. The 5-year freedom from stroke in patients undergoing conventional sternotomy was 95.5% compared with 97.5% in the less invasive cohort (log-rank = 0.81; $P = .369$). Freedom from repair failure at 5 years was 95.4% overall, and it was 95.1% in era 1 and 95.5% in era 2 ($P = .707$) (Figure 5). Overall 5-year survival was 91.6% and 89.4% in era 1 and 94.2% in era 2 ($P = .006$) (Figure 6). However, after adjustment for age, sex, and era, the artificial cordal repair technique was not significantly associated with 5-year survival (HR, 1.71; 95% confidence interval, 0.91 to 3.24; $P = .097$).

Within the repair failures during all of follow-up, 25 patients underwent reoperations, and 6 were found to have greater than moderate MR at late follow-up. The cause of reoperation was endocarditis in 3 of 25 patients, SAM in 4 of 25 patients, and recurrent MR in 18 of 25 patients (Supplemental Table 2).

On univariate analysis, the only significant risk factor for repair failure was higher preoperative systolic pulmonary artery pressures (HR, 1.04; $P = .004$). There was also an increased risk of repair failure with anterior leaflet involvement (isolated anterior leaflet prolapse or bileaflet prolapse), but this analysis did not reach statistical significance (HR, 1.79; $P = .099$) (Table 4).

Comment

This study demonstrates that a nearly universal artificial cordal repair approach to MV repair for degenerative MV disease is associated with excellent short- and long-term outcomes that are similar to those seen with a tailored approach using both resectional and artificial cordal repair techniques. Perioperative and late results in both eras were characterized by a low incidence of late valve failure, early or late SAM, and durable MV repair.

MV repair for degenerative MV disease has significant well-documented benefits compared with MV replacement.[16,17] The principles of MV repair involve optimizing annular size and shape with an annuloplasty ring, maximizing leaflet coaptation, and maintaining physiologic leaflet systolic and diastolic motion without creating stenosis. Along with annuloplasty ring placement, resection of the prolapsed leaflet tissue with a quadrangular or triangular resection has demonstrated long-term efficacy and durability by adhering to these principles.[8,18] Our early approach to MV repair largely involved leaflet resection when feasible and reserved artificial cordal repair for anterior leaflet prolapse. However, as we gained experience with the artificial cordal repair approach, we migrated to a nearly universal artificial cordal repair approach for patients with degenerative MR. We were able to achieve similar excellent repair rates with less operative complexity. Although several irrevocable decisions must

Table 3. Perioperative and Late Outcomes

Outcomes	Overall N=843	Era 1 n = 405	Era 2 n = 438	*P* Value
Perioperative outcomes				
Predischarge MR	(822/843)	(390/405)	(432/438)	.408
None or trace	782 (95)	368 (94)	414 (96)	
Mild	39 (5)	21 (5)	18 (4)	
Moderate	1 (0.1)	1 (0.2)	0 (0)	
Severe	0 (0)	0 (0)	0 (0)	
Stroke	5 (0.6)	2 (0.5)	3 (0.7)	.537
Discharge on anticoagulation	245 (29)	105 (26)	140 (32)	.054
Predischarge MV gradient	(656/843)	(256/405)	(400/438)	.999
	4 (3-5)	4 (3-6)	4 (3-5)	
Operative mortality	4 (0.5)	2 (0.5)	2 (0.5)	.941
Late outcomes				
Five-y freedom from event, %				
Endocarditis	99.4	99.3	99.7	.604
Stroke	96.3	96.8	95.3	.538
Repair failure	95.4	95.1	95.5	.707
Survival	91.6	89.4	94.2	.006
Long-term outcomes				
Change in EF (%)	0 (−5 to 5)	0 (−5 to 5)	0 (−5 to 5)	.132
Change in sPAP (mm Hg)	−1 (−10 to 7)	0 (−8 to 10)	−2 (−11 to 6)	.268
NYHA functional class (n/N, %)	(697/843)	(403/405)	(294/438)	.034
1	86	83	88	
2	11	11	10	
3	2	4	2	
4	1	2	1	
Mean gradient	3 (3-5)	3 (3-4)	3 (3-5)	.212
Follow-up MR	271/661 (41)	140/303 (46)	131/358 (37)	.012
Mild	194 (29)	94 (31)	100 (28)	.385
Moderate	60 (9)	34 (11)	26 (7)	.078
Severe	17 (3)	12 (4)	5 (1)	.038

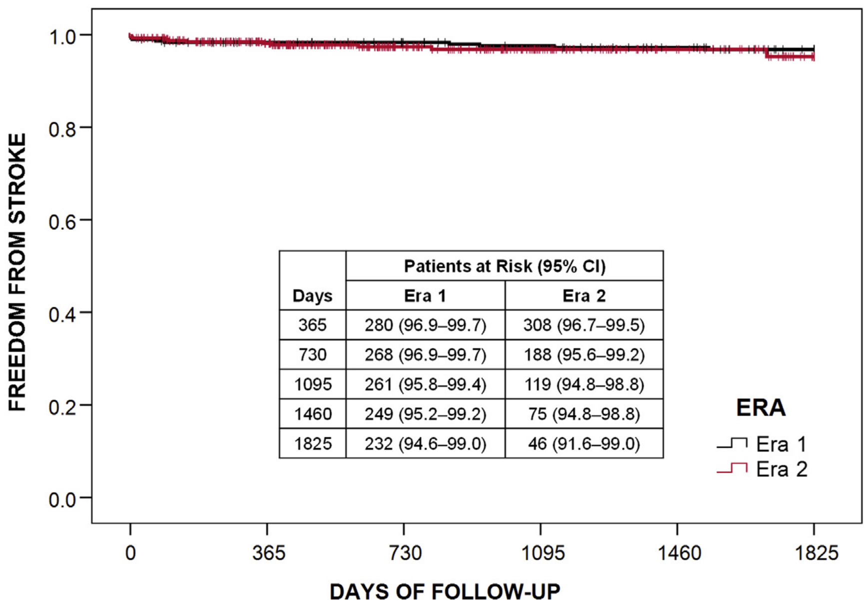
Data presented as %, frequency (%), mean ± SD, or median (interquartile range).

EF, ejection fraction; MR, mitral regurgitation; MV, mitral valve, NYHA, New York Heart Association; sPAP, systolic pulmonary artery pressure.

be made with a resectional approach, including type of resection, amount of resection, and the decision to perform a sliding plasty, placing artificial ePTFE cords in the prolapsed segment of the MV has the potential to be reversed, is simpler, is reproducible, and can be used in all patients with degenerative MR. After placing cords, the surgeon can perform a saline test to evaluate the repair and adjust or supplement the cords as necessary. We believe that the simplicity of the artificial cordal repair approach compared with a resectional approach is responsible for the 12- and 9-minute shorter cardiopulmonary bypass and myocardial ischemia times in the most recent era. A universal artificial cordal repair approach does not require leaflet resection and therefore abolishes the risk of repair failure related to suture line disruption. Furthermore, annular plication can be associated with circumflex artery kinking, and this risk is also mitigated by a universal artificial cordal repair approach.[19,20]

Universally using the artificial cordal repair approach has led to less complex intraoperative decision making to achieving a successful repair because each repair is systemically similar: (1) intraoperatively determine the location of leaflet prolapse, (2) resuspend the prolapsed/affected segments with ePTFE artificial cords, (3) size and insert an annuloplasty ring according to the size of the anterior MV leaflet, and (4) confirm coaptation with a saline test and adjust the length of ePTFE cords accordingly. We have found this to be a reproducible strategy in all variations of degenerative MV disease, including Barlow disease.

Despite concern that resuspension with cords in the setting of excess leaflet tissue would lead to a high incidence of postoperative SAM, we found a similar rate of early SAM and late SAM with both approaches. As previously demonstrated, SAM can largely be prevented by careful leaflet positioning and annuloplasty ring sizing.[21] In patients who do have intraoperative SAM and do not respond to volume loading over time, we do not hesitate to resume bypass and shorten the posterior leaflet cords. If necessary, we also perform a curtain stitch at the



Days	Patients at Risk (95% CI)	
	Era 1	Era 2
365	280 (96.9–99.7)	308 (96.7–99.5)
730	268 (96.9–99.7)	188 (95.6–99.2)
1095	261 (95.8–99.4)	119 (94.8–98.8)
1460	249 (95.2–99.2)	75 (94.8–98.8)
1825	232 (94.6–99.0)	46 (91.6–99.0)

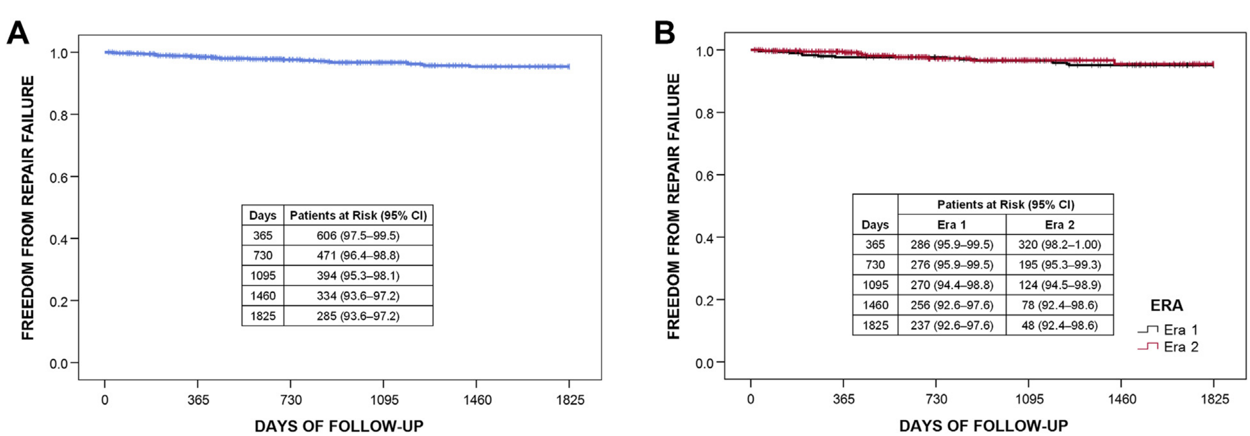
Figure 4. The 5-year freedom from cerebrovascular accident by era. Rates were similar between era 1 and era 2. (CI, confidence interval.)

anterolateral commissure.[22] After these maneuvers, if there remains evidence of significant SAM, we replace the valve. However, only 1 patient in our series required intraoperative MV replacement for SAM.

In simplifying MV repair with artificial cordal repair techniques, teaching MV repair to trainees is readily achievable. In the first 3 years of our integrated 6-year training program, all trainees learn the basic principles of MV repair using artificial cordal repair techniques and have the opportunity to perform basic MV repairs such as isolated P_2 prolapse. By graduation, the trainees will have seen and performed MV repair for various causes and disorders of degenerative MV disease and are able to execute these repairs successfully and feel comfortable with independently repairing the full spectrum of degenerative MV disease.

Artificial cordal repair has previously been demonstrated to be durable for 25 years. David and colleagues[10] described 95% freedom from reoperation in 606 patients with degenerative MV disease and greater than 95% freedom from reoperation with isolated posterior leaflet prolapse. There were no cases of cordal rupture. In our experience, there were only 2 cases of late cordal rupture, 1434 and 3884 days after the initial operation, respectively. Other causes of MV reoperation included progressive leaflet fibrosis and restriction in 7 (28%) patients, progressive degenerative disease in 5 (20%) patients, and SAM in 4 (16%) patients.

Other groups have also demonstrated excellent outcomes with an artificial cordal repair approach.[21,23] Lawrie and colleagues[21] described 662 patients, with 497 consecutive repairs performed using artificial cordal repair techniques. At a mean of 2.3 years, there was a 3% incidence of repair failure. Moreover, in comparing artificial cordal repair with resectional techniques, Falk and colleagues[12] performed a randomized controlled trial and



A

Days	Patients at Risk (95% CI)
365	606 (97.5–99.5)
730	471 (96.4–98.8)
1095	394 (95.3–98.1)
1460	334 (93.6–97.2)
1825	285 (93.6–97.2)

B

Days	Patients at Risk (95% CI)	
	Era 1	Era 2
365	286 (95.9–99.5)	320 (98.2–1.00)
730	276 (95.9–99.5)	195 (95.3–99.3)
1095	270 (94.4–98.8)	124 (94.5–98.9)
1460	256 (92.6–97.6)	78 (92.4–98.6)
1825	237 (92.6–97.6)	48 (92.4–98.6)

Figure 5. The 5-year freedom from repair failure (mitral valve reoperation or greater than moderate mitral regurgitation) of (A) the overall cohort of patients and (B) by era. This rate was similar between era 1 and era 2. (CI, confidence interval.)

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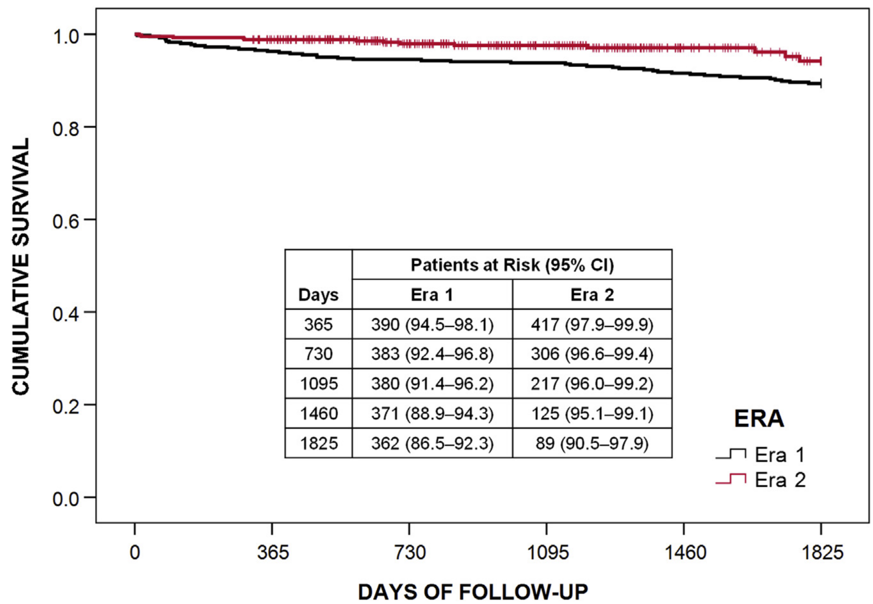
Figure 6. Kaplan-Meier 5-year survival curves after mitral valve repair for degenerative mitral regurgitation. (CI, confidence interval.)



demonstrated equivalent clinical outcomes, but with a 1.7-mm deeper surface of coaptation with artificial cordal approaches.

Our current repair strategy is to use an artificial cordal repair approach in nearly all patients. However, in rare instances of Barlow disease with extreme excessive leaflet tissue, resection to debulk the leaflet tissue is used in conjunction with artificial cords. In era 2, 2% of patients underwent resection, and these patients had Barlow valves with excessive leaflet tissue.

Table 4. Univariate Predictors of Repair Failure

Predictors	Hazard Ratio	95% Confidence Interval	*P* Value
Age (per year)	0.99	0.96-1.02	.600
Female	0.76	0.35-1.70	.500
Preoperative EF (per %)	0.99	0.95-1.04	.72
Preoperative sPAP (per mm Hg)	**1.04**	**1.01-1.06**	**.004**
Isolated P_2 prolapse	0.61	0.27-1.42	.254
Isolated anterior prolapse	1.74	0.61-5.00	.303
Anterior leaflet involvement	1.79	0.90-3.60	.099
Number of prolapsed segments	1.05	0.82-1.34	.704
Less invasive	1.02	0.49-2.15	.956
Artificial cordal technique	1.35	0.62-2.96	.450
Number of cords	1.13	0.95-1.35	.154
Ring size	1.00	0.89-1.11	.937
Era (era 1 vs era 2)	1.04	0..47-2.34	.920

Bold text indicates statistical significance ($P < .05$).

EF, ejection fraction; sPAP, systolic pulmonary artery pressure.

Study Limitations

This study is a retrospective analysis with the limitations associated with this study design. A total of 11% of patients were lost to clinical or echocardiographic follow-up, and we are unable to determine their outcomes. Furthermore, as part of a retrospective analysis, there are potential confounders such as patient management and surgeon experience. This study was performed over a relatively long period (2004 to 2017) by a single, experienced surgeon at a single institution. However, our experience in training residents to perform MV repair using artificial cordal repair techniques anecdotally supports the adoptability and reproducibility of this approach. Further studies are necessary to examine the reproducibility of a universal artificial cordal repair approach by surgeons less experienced with MV repair.

In this analysis, eras were studied consecutively rather than concurrently. There may be differences between eras that contribute to the outcomes, including operative timing, patient optimization, and referral patterns. Fewer patients in era 2 had available clinical and echocardiographic follow-up beyond 5 years, and therefore, the outcomes may be limited by sample size. Long-term follow-up is necessary to continue to evaluate repair durability and determine the robustness of a universal artificial cordal repair approach.

Conclusion

Degenerative MV repair can almost exclusively be performed with artificial cordal repair and yields excellent outcomes. A universal artificial cordal repair approach for patients with degenerative MR simplifies MV repair and is reproducible and durable.

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INVITED COMMENTARY

Check for updates

A systematic approach of mitral reconstruction began with the seminal work of Professor Alain Carpentier.[1] Most of his techniques for degenerative prolapse utilized resection of the offending segments. Beginning in 1986, Robert Frater first experimentally demonstrated the utility of polytetrafluoroethylene neochords in replacing chordae tendinae.[2] Shortly thereafter, Tirone David began his extensive clinical experience in resuspending prolapsing segments, particularly of the anterior leaflet.[3] This was later extended to virtually all prolapsing segments by Perier and Mohr.[4,5] The subsequent respect vs resect management strategies began to dichotomize the literature until recent views of equipoise.

In the current contribution to *The Annals*, Pasrija and colleagues[5] share details of their 13-year experience in mitral reconstruction of 847 patients at the University of Maryland. Era 1 consisted of 405 patients operated from January 2004 through June 2011 with resection techniques. In era 2, 438 patients were reconstructed with only neochords. Both eras enjoyed excellent repair rates, low complications, and seemingly durable results. Interestingly, the minimally invasive platform was virtually abandoned in the most recent era. The authors' contention was that uniform use of neochords to correct prolapse gave equivalent results to resection, whereas simplifying teaching residents and avoiding annular

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