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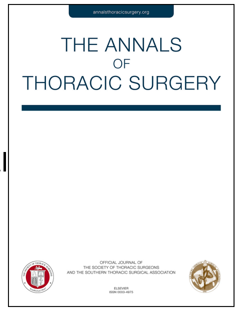

Degenerative Mitral Valve Repair Simplified: An Evolution to Universal Artificial Cordal Repair

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Running Head: DMR Simplified

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Abstract

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, while cordal repair offers a simpler, easily-reproducible repair. Our approach has evolved from resectional to cordal over time, and we compared outcomes between the eras.

Methods

Clinical and echocardiographic outcomes of all patients undergoing MV repair for degenerative mitral regurgitation (MR) from 1/2004-9/2017 were reviewed. Patients were stratified by era: from 1/2004-6/2011 (Era-1, n=405), resectional techniques were utilized in 62% and artificial cordal in 38%. From 7/2011-9/2017 (Era-2, n=438), artificial cordal repair was utilized 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 (CPB) time and cross-clamp times were shorter in Era-2 (CPB: 109 [92-128] vs. 97 [76-121], P<0.001; Cross-clamp: 88 [73-106] vs. 79 [61-99], P<0.001). Pre-dismissal echocardiography demonstrated none/trace MR in 95%, mild in 4.7%, and moderate in 0.3% of patients. Operative mortality was similar in the eras (0.5% vs 0.5%, P>0.999). Five-year freedom from repair failure (95.1% vs 95.5%, P=0.707), stroke (96.8% vs 95.3%, P=0.538), and endocarditis (99.3% vs 99.7%, P=0.604) were similar between the eras.

Conclusions

Artificial cordal repair for all patients with degenerative MR simplifies MV repair and yields equivalent, excellent outcomes compared to 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 replacement and societal guidelines recommend MV repair for patients with severe primary mitral regurgitation (MR) (3).

Techniques 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 frequently require additional maneuvers including sliding plasty, annular plication, chordal transfer, anterior leaflet resection, commissuroplasty and others (5-8). While excellent long-term results have been reported utilizing these techniques, resectional repair requires a complex patient-tailored approach that can be difficult to reproduce and teach. Frater and colleagues first reported experimental and clinical use of expanded polytetrafluorethylene (ePTFE) cords to achieve mitral valve repair by replacing ruptured or elongated native chordae tendinae (9). This artificial cordal repair MV repair strategy has documented excellent mid- and long-term outcomes (10-12).

At our institution, we predominantly utilized 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 similar excellent outcomes as a tailored approach utilizing 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 (751/843 patients) with clinical follow-up available in 85% (718/843) and echocardiographic follow-up available in 79% (663/843). 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 utilized in 62% (252/405) of patients and artificial cordal repair in 38% (153/405). From July 2011 to September 2017 (Era-2), artificial cordal repair techniques were utilized in 98% (431/438) of patients (Figure 2).

Operative Technique and Postoperative Management

Procedures were performed through a median sternotomy with a limited skin incision or via small right thoracotomy (less-invasive) (13). Utilization of the less-invasive operative approach decreased over time as 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 utilized 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 utilized. The aorta was directly clamped and only antegrade cardioplegia was utilized.

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(s) of the MV. ePTFE cordal pairs are spaced 3-4 mm apart on the free edge of the prolapsed segment(s). Our practice evolved from use of flexible partial annuloplasty bands to the universal use of non-planar semi-rigid complete annuloplasty rings over time.

All patients undergoing a CryoMaze procedure were discharged on anticoagulation(14). Isolated MV repair patients were discharged on aspirin alone.

Follow-up Echocardiography

MR was assessed intraoperatively using transesophageal echocardiography in all patients. Predischarge echocardiography was performed in 828/843 (98%) patients, with semi-quantitative assessment of MR grade, along with assessment of MV gradient. MR was classified as none/trace, mild, moderate, and severe according to 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 (NYHA) class, and mean gradient.

Statistical Analysis:

Data were analyzed using SAS Statistical Software (v. 9.3, Cary, NC). Continuous variables are presented as mean ± standard deviation for normally distributed variables or median with interquartile range for non-normally distributed variables and were compared with a Student's t-test or Mann-Whitney U test, as appropriate. Categorical variables are presented as frequency (%) and compared using the chi-square or Fisher's exact test. Change in EF and sPAP from before surgery to follow-up echocardiography by era group were evaluated using repeated measures ANOVA. Freedom from repair failure, stroke, and endocarditis was calculated using the Kaplan-Meier method from time of operation to failure or last known follow-up. Differences were compared using the log-rank test. delete Sensitivity analyses examined freedom from repair failure, stroke, and endocarditis by era with death as a competing risk, but found no meaningful differences from the Kaplan-Meier survival analyses. In order 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, gender, and era.

Results

Patient Characteristics

The mean age was 61 ± 13 years, 65% of patients were male, and 87% were Caucasian. 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 mmHg) in 31% (Table 1).

Degenerative disease affected the posterior leaflet in 66%, the anterior leaflet in 8%, and both leaflets in 26% of patients. Resectional techniques were utilized in 28% of cases overall. There was a marked progression away from resectional techniques towards artificial cordal repair techniques over time, and artificial cordal repair techniques predominated after 2007. A less-invasive operative approach was utilized in 26% of cases, but also decreased over time, with >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 vs 59 ± 13 years, P<0.001) and less likely to be male (62% vs 69%, P=0.039). Patients in Era-2 were more likely to have a normal left ventricular ejection fraction (72% vs 57%, P<0.001) and normal systolic pulmonary artery pressures (76% vs 64%, P=0.003).

Operative Characteristics

Of 847 patients with degenerative MV disease, MV repair was performed in 843/847 (99.5%). During Era-1, 62% of patients underwent mitral valve repair with resectional techniques and 38% with artificial cordal repair techniques. Resection was performed with a triangular resection in 56%, quadrangular resection in 25%, and leaflet imbrication in 19% of patients. A sliding plasty performed in 19% of resections. During Era-2, 98% of patients underwent artificial cordal repair techniques and 2% underwent resection (P<0.001). 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 (831/843). Mean ring size was 31±3 in Era-1 and 32±3 in Era-2 (P=0.099). A partial flexible ring was utilized in 51% of patients and a complete non-planar semi-rigid ring was utilized in 47% of patients during Era-1. In contrast, in Era-2, a complete non-planar semi-rigid ring was utilized in 99% of patients (*P*<0.001).

Compared to Era-1, median cardiopulmonary bypass (CPB) time and myocardial ischemia time were shorter in Era-2 (CPB: 109 [92-128] vs 97 [76-121] min, *P*<0.001; myocardial ischemia: 88 [73-106] vs. 79 [61-99] min, *P*<0.001). These differences remained significant for isolated MV repairs without concomitant procedures and when comparing only those undergoing full sternotomy. Despite the near-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*=0.488). There was also no significant difference in the incidence of intraoperative SAM when comparing resectional mitral valve repair to artificial cordal repair approaches (3% vs 4%, *P*=0.310).

Perioperative Outcomes

At discharge, 95% (782/843) of patients had none/trace MR, 4.8% (39/843) had mild MR, and 0.1% (1/843) had moderate MR. No patients were discharged with greater than moderate MR. Predischarge MR grades were similar between the two eras (Figure 3). Mean gradient at discharge was also similar between Era-1 and Era-2 (4 vs 4 mmHg, *P*=0.999) (Table 3).

Five patients (0.6%) had a postoperative CVA. Two patients (0.2%) had a disabling stroke (modified Rankin score ≥ 2). The incidence of in-hospital postoperative CVA was similar between Era-1 and Era-2 (0.5% vs 0.7%, *P*>0.999).

Operative mortality was 0.5% in both eras (*P*>0.999). There were 4 in-hospital mortalities, all secondary to multi-system 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) and was similar between the two eras. Preoperative characteristics including atrial fibrillation (HR = 0.66, 95% CI: 0.15-2.87, *P*=0.582) were not predictive of late stroke. Five-year freedom from stroke in patients undergoing conventional sternotomy was 95.5% compared to 97.5% in the less-invasive cohort (Log Rank = 0.81, *P*=0.369). Freedom from repair failure at 5 years was 95.4%

overall and was 95.1% in Era-1 and 95.5% in Era-2 (P=0.707; Figure 5). Overall 5-year survival was 91.6%, 89.4% in Era-1 and 94.2% in Era-2 (P=0.006; Figure 6). However, after adjustment for age, gender, and era, the artificial cordal repair technique was not significantly associated with 5-year survival (HR = 1.71, 95% CI: 0.91-3.24, P=0.097)

Within the repair failures during all of follow-up, 25 patients underwent reoperations and 6 were found to have >moderate MR at late follow-up. The etiology of reoperation was endocarditis in 3/25 patients, SAM in 4/25 patients, and recurrent MR in 18/25 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=0.004). 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=0.099; Table 4).

Comment

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

MV repair for degenerative MV disease has significant well-documented benefits compared to 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, reserving artificial cordal repair for anterior leaflet prolapse. However, as we gained experience with the artificial cordal repair approach, we migrated to a near universal artificial cordal repair approach for patients with degenerative MR. We were able to achieve similar excellent repair rates with less operative complexity. While several irrevocable decisions must 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, reproducible, and can be utilized 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 to a resectional approach is responsible for the 12 and 9 minute shorter CPB 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 utilizing the artificial cordal repair approach has led to less complex intraoperative decision making to achieving a successful repair, as 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 based on the size of the anterior MV leaflet, 4) confirm coaptation with a saline test and adjust length of ePTFE cords accordingly. We have found this to be a reproducible strategy in all variations of degenerative MV disease, including Barlow's 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 don't respond to volume-loading over time, we do not hesitate to go back on bypass and shorten the posterior leaflet cords. If necessary, we also perform a curtain stitch at the 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 mitral valve replacement for SAM.

In simplifying MV repair with artificial cordal repair techniques, teaching MV repair to trainees is readily achievable. In the first three years of our integrated six-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 P2 prolapse. By graduation, the trainees will have seen and performed MV repair for various etiologies and pathologies of degenerative MV disease and are able to successfully execute these repairs and feel comfortable with independently repairing the full spectrum of degenerative mitral valve disease.

Artificial cordal repair has previously been demonstrated to be durable for 25 years. David et al. described a 95% freedom from reoperation in 606 patients with degenerative mitral valve disease, and >95% freedom from reoperation with isolated posterior leaflet prolapse. There were no cases of cordal rupture. In our experience, only there were only 2 cases of late cordal rupture, 1434 and 3884 days after the initial operation. 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 et al. described 662 patients, with 497 consecutive repairs performed utilizing artificial cordal repair techniques. At a mean of 2.3 years, there was a 3% incidence of failure. Moreover, in comparing artificial cordal repair to resectional techniques, Falk et al. performed a randomized control trial and demonstrated equivalent clinical outcomes but a 1.7mm deeper surface of coaptation with artificial cordal approaches(12).

Our current repair strategy is to utilize an artificial cordal repair approach in nearly all patients. However, in rare instances of Barlow's 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's valves with excessive leaflet tissue.

Limitations

This study is a retrospective analysis with the associated limitations. Eleven percent 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 large time period (2004-2017) by a single, experienced surgeon at a single institution. However, our experience training residents to perform mitral valve 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 mitral valve 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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Table 1: Patient Characteristics

	Overall *N*=843	**Era-1** *n*=405	**Era-2** *n*=438	***P*-value**
Demographics				
Age (years)	61 ± 12	59 ± 13	62 ± 12	<0.001
Male	549 (65%)	278 (69%)	271 (62%)	0.039
Race				0.504
African-American	75 (9%)	35 (9%)	40 (9%)	
Caucasian	733 (87%)	359 (89%)	374 (86%)	
Other	35 (4%)	10 (2%)	19 (5%)	
Comorbid Conditions				
Atrial Fibrillation	236 (28%)	116 (28%)	120 (28%)	0.718
Diabetes	66 (8%)	27 (7%)	39 (9%)	0.292
Dyslipidemia	399 (47%)	205 (51%)	194 (45%)	0.137
Hypertension	459 (54%)	234 (58%)	225 (52%)	0.133
LVEF				<0.001
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	<0.001
sPA Pressure	(594/843)	(334/405)	(260/438)	0.003
Normal (<40 mmHg)	412 (69%)	215 (64%)	197 (76%)	
Elevated (>40 mmHg)	182 (31%)	119 (36%)	63 (24%)	
Previous Cardiac Surgery	34 (4%)	9 (2%)	25 (6%)	0.007
Previous MV Surgery	12 (2%)	0 (0%)	12 (3%)	<0.001
Previous Sternotomy	27 (3%)	7 (2%)	20 (5%)	0.019
NYHA Class III or IV	336 (40%)	165 (41%)	171 (39%)	0.692
STS PROM (%)	(566/843) 0.51 (0.31-1.00)	(275/405) 0.44 (0.29-1.08)	(290/438) 0.57 (0.32-0.99)	0.818

EF, ejection fraction; LVEF, left ventricular ejection fraction; NYHA, New York Heart Association; sPA, systolic pulmonary artery; STS PROM, Society of Thoracic Surgeons predicted risk of mortality

Data presented as frequency (percent), mean ± standard deviation, or median (IQR)

Table 2: Operative Details

	Overall *N*=843	**Era-1** *n*=405	**Era-2** *n*=438	***P*-value**
Less-Invasive	223 (26%)	193 (48%)	30 (7%)	<0.001
Concomitant Procedures	308 (37%)	146 (36%)	163 (37%)	0.778
CryoMaze	198 (24%)	100 (25%)	98 (24%)	0.704
CABG	102 (12%)	57 (14%)	45 (10%)	0.096
TV Repair	83 (10%)	25 (6%)	58 (14%)	<0.001
CPB (mins)	105 (87-126)	109 (92-128)	97 (76-121)	<0.001
Isolated MV CPB (mins)	94 (76-113)	100.5 (88-118)	83 (70-101)	<0.001
Myocardial Ischemia (mins)	82 (66-103)	88 (73-106)	79 (61-99)	<0.001
Isolated MV Myocardial Ischemia (mins)	73 (60-88)	79 (66-94)	65.5 (56-80)	<0.001
Intraoperative SAM	31 (4%)	13 (3%)	18 (4%)	0.488
Req. re-arrest	11 (36%)	4 (31%)	7 (39%)	0.641
Artificial Cordal Repair	583 (69%)	153 (38%)	430 (98%)	<0.001
Number of cordal pairs	3 (1-4)	2 (0-3)	4 (3-4)	<0.001
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%)	<0.001
Triangular Resection	146 (17%)	140 (56%)	6 (75%)	0.281
Quadrangular Resection	62 (7%)	62 (25%)	0 (0%)	0.107
Imbrication alone	50 (6%)	49 (19%)	1 (0.1%)	<0.001
Adjunctive Techniques				
Imbrication	27 (3%)	10 (2%)	17 (4%)	0.328
Sliding Plasty	49 (6%)	48 (12%)	1 (0.2%)	<0.001
Commissural Closure-Anterior	41 (5%)	9.0 (2%)	32 (7%)	<0.001
Commissural Closure-Posterior	162 (19%)	88 (22%)	74 (17%)	0.073

Cleft Closure	256 (30%)	123 (30%)	133 (30%)	0.999
Annuloplasty Components				<0.001
Complete semi-rigid	641 (76%)	208 (51%)	433 (99%)	
Partial flexible	189 (22%)	189 (47%)	0 (0%)	
No Ring	12 (2%)	8 (2%)	4 (1%)	
Ring Size				0.032
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%)	

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

Data presented as frequency (percent), mean ± standard deviation, or median (IQR)

Table 3: Perioperative and Late Outcomes

	Overall *N*=843	**Era-1** *n*=405	**Era-2** *n*=438	***P*-value**
Perioperative Outcomes				
Predischarge MR	(822/843)	(390/405)	(432/438)	0.408
None/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%)	0.537
Discharge on Anticoagulation	245 (29%)	105 (26%)	140 (32%)	0.054
Predischarge MV Gradient	(656/843) 4 (3-5)	(256/405) 4 (3-6)	(400/438) 4 (3-5)	0.999
Operative Mortality	4 (0.5%)	2 (0.5%)	2 (0.5%)	0.941
Late Outcomes				
Five-year Freedom from Event				
Endocarditis	99.4%	99.3%	99.7%	0.604
Stroke	96.3%	96.8%	95.3%	0.538
Repair Failure	95.4%	95.1%	95.5%	0.707
Survival	91.6%	89.4%	94.2%	0.006
Long-Term Outcomes				
Change in EF (%)	0 (-5–5)	0 (-5–5)	0 (-5–5)	0.132
Change in sPAP (mmHg)	-1 (-10–7)	0 (-8–10)	-2 (-11–6)	0.268
NYHA Class	(697/843)	(403/405)	(294/438)	0.034
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)	0.212
Follow-up Mitral Regurgitation	271/661 (41%)	140/303 (46%)	131/358 (37%)	0.012
Mild	194 (29%)	94 (31%)	100 (28%)	0.385
Moderate	60 (9%)	34 (11%)	26 (7%)	0.078
Severe	17 (3%)	12 (4%)	5 (1%)	0.038

MR, mitral regurgitation; MV, mitral valve

Table 4: Univariate Predictors of Repair Failure

	Hazard Ratio	***95% CI***	***p-value***
Age (per year)	0.99	0.96-1.02	0.600
Female	0.76	0.35-1.70	0.500
Preoperative EF (per %)	0.99	0.95-1.04	0.72
Preoperative sPA (per mmHg)	**1.04**	**1.01-1.06**	**0.004**
Isolated P2 Prolapse	0.61	0.27-1.42	0.254
Isolated Anterior Prolapse	1.74	0.61-5.00	0.303
Anterior Leaflet Involvement	1.79	0.90-3.60	0.099
Number of Prolapsed Segments	1.05	0.82-1.34	0.704
Less Invasive	1.02	0.49-2.15	0.956
Artificial Cordal Technique	1.35	0.62-2.96	0.450
Number of Cords	1.13	0.95-1.35	0.154
Ring Size	1.00	0.89-1.11	0.937
Era (Era-1 vs. Era-2)	1.04	0..47-2.34	0.920

Figure Legends

Figure 1: Consort diagram describing mitral valve operations performed by a single surgeon between January 1, 2004 and September 1, 2017.

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

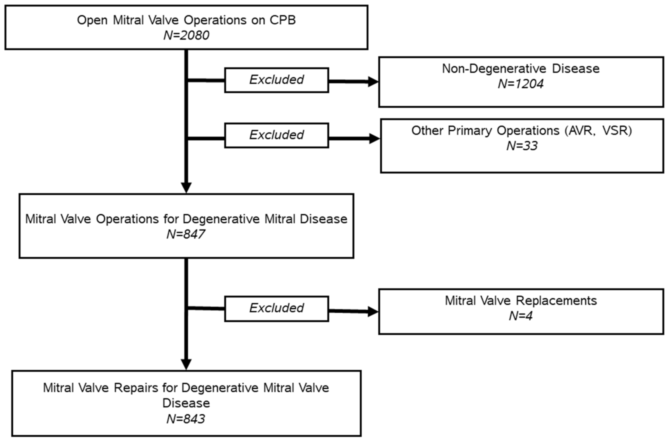
Figure 3: Preoperative, intraoperative, and early postoperative mitral regurgitation of the overall cohort of patients.

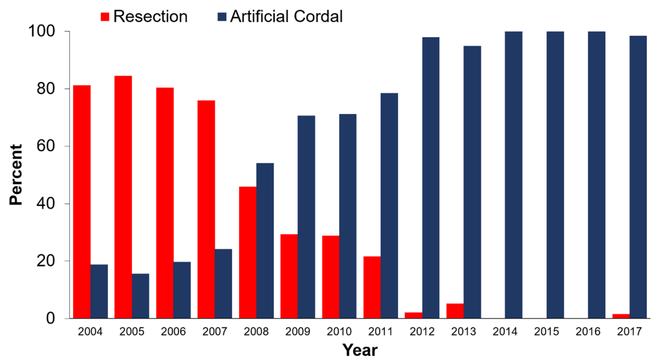
Figure 4: Five-year freedom from cerebrovascular accident by era, similar between Era-1 and Era-2.

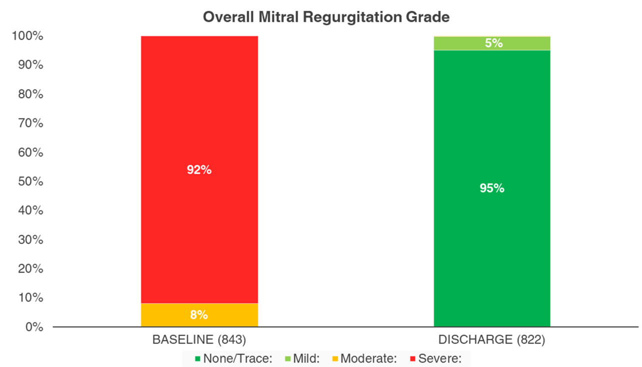
Figure 5: Five-year freedom from repair failure (mitral valve reoperation or >moderate mitral regurgitation) of the overall cohort of patients (A) and by era (B), which was similar between Era-1 and Era-2.

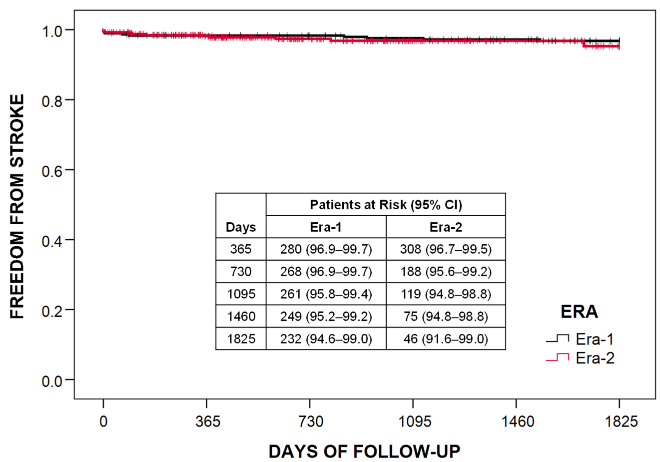
Figure 6: Kaplan-Meier 5-year survival curves after mitral valve repair for degenerative mitral regurgitation.

Supplemental Figure 1: The use of a less-invasive, right thoracotomy incision over time

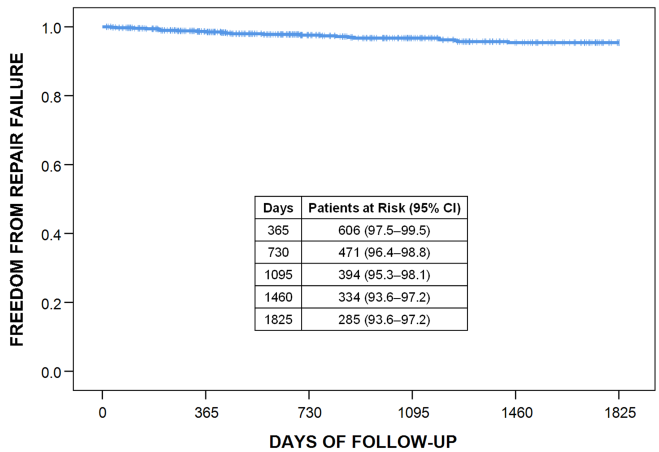

Open Mitral Valve Operations on CPB
N=2080
Excluded
Non-Degenerative Disease
N=1204
Excluded
Other Primary Operations (AVR, VSR)
N=33
Mitral Valve Operations for Degenerative Mitral Disease
N=847
Excluded
Mitral Valve Replacements
N=4
Mitral Valve Repairs for Degenerative Mitral Valve Disease
N=843

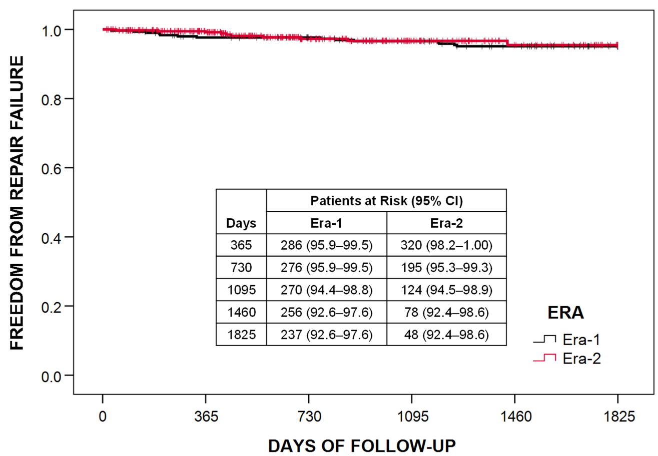

Resection
Artificial Cordal
100
80
60
40
20
0
Percent
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year

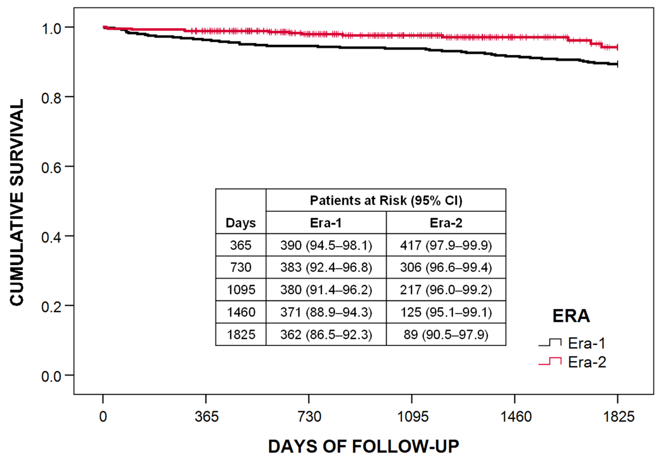

Overall Mitral Regurgitation Grade
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
92%
8%
5%
95%
BASELINE (843)
DISCHARGE (822)
None/Trace:
Mild:
Moderate:
Severe:



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)


FREEDOM FROM REPAIR FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
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)
0
365
730
1095
1460
1825
DAYS OF FOLLOW-UP


FREEDOM FROM REPAIR FAILURE
1.0
0.8
0.6
0.4
0.2
0.0
Patients at Risk (95% CI)
Days | 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)
ERA
Era-1
Era-2
0
365
730
1095
1460
1825
DAYS OF FOLLOW-UP


1.0
0.8
0.6
0.4
0.2
0.0
CUMULATIVE SURVIVAL
Patients at Risk (95% CI)
Days
Era-1
Era-2
365
390 (94.5–98.1)
417 (97.9–99.9)
730
383 (92.4–96.8)
306 (96.6–99.4)
1095
380 (91.4–96.2)
217 (96.0–99.2)
1460
371 (88.9–94.3)
125 (95.1–99.1)
1825
362 (86.5–92.3)
89 (90.5–97.9)
ERA
Era-1
Era-2
0
365
730
1095
1460
1825
DAYS OF FOLLOW-UP