Combined aortic root replacement and mitral valve surgery: The quest to preserve both valves

Hoda Javadikasgari, MD,^a Eric E. Roselli, MD,^a Muhammad Aftab, MD,^b Rakesh M. Suri, MD, D. Phil,^a Milind Y. Desai, MD,^a Mitra Khosravi, BS,^a Frank Cikach, BS,^a Monica Isabella, MD,^a Jay J. Idrees, MD,^a Sajjad Raza, MD,^a Bassman Tappuni, MD,^a Brian P. Griffin, MD,^a Lars G. Svensson, MD, PhD,^a and A. Marc Gillinov, MD^a

ABSTRACT

Objectives: Coexisting aortic root and mitral valve pathology is increasingly recognized among patients undergoing surgery. We characterized the pathology and surgical outcomes of patients with combined aortic root and mitral disease.

Methods: From 1987 to 2016, 118 patients (age 52.40 ± 17.71 years) underwent concomitant aortic root and mitral procedures (excluding aortic stenosis, endocarditis, and reoperations). Aortic root pathologies included degenerative aneurysm (94%) and aortic dissection (6%). The aortic valve was bicuspid in 15% of patients and had normally functioning tricuspid leaflets in 23% of patients. Marfan syndrome was present in 34 patients (29%). Degenerative mitral disease predominated (78%). Mitral procedures were repair (86%) and replacement (14%), and root procedures were valve-preserving root reimplantation (36%), Bentall procedure (47%), and homograft root replacement (17%). In the last 10 years, the combination of valve-preserving root reimplantation and mitral repair has increased to 50%. Kaplan–Meier and competing risk analyses were used to estimate survival and reoperation.

Results: There were 2 (1.7%) operative deaths with survival of 79% and 71% at 10 and 15 years, respectively, and reoperation rates of 4.7% and 12% after 5 and 10 years, respectively. There were no operative deaths in patients with combined valve-preserving root reimplantation and mitral repair, with survival of 89% and reoperation rate of 7.8% at 10 years. Among patients with Bentall/homograft and mitral operation, survival was 73% and reoperation was 9.8% at 10 years.

Conclusions: In patients with aortic root and mitral pathology, combined surgical risk is low and valve durability is high. When possible, valve-preserving root reimplantation and mitral repair should be considered to avoid prosthesis degeneration, anticoagulation, and lifestyle limitations. (J Thorac Cardiovasc Surg 2017;153:1023-30)

Trends in operative strategy in patients undergoing combined operations.

Central Message

When possible, VPRR and MV repair should be considered in aortic root and MV pathology.

Perspective

Surgeons increasingly are encountering patients with coexisting aortic root and MV pathology. Combined aortic root and MV surgery is safe and associated with excellent long-term survival and durability. When possible, preserving both valves should be used to avoid prosthesis degeneration, anticoagulation, and lifestyle limitations.

See Editorial Commentary page 1031.

See Editorial page 1021.

From the ^aAorta Center, Valve Center, Departments of Thoracic and Cardiovascular Surgery and Cardiovascular Medicine, Heart and Vascular Institute, Cleveland Clinic, Cleveland, Ohio; and ^bDepartment of Surgery, Division of Cardiothoracic Surgery, University of Colorado, Denver, Colo.

Read at The American Association for Thoracic Surgery Aortic Symposium 2016, New York, New York, May 12-13, 2016.

Received for publication May 30, 2016; revisions received Dec 28, 2016; accepted for publication Jan 18, 2017; available ahead of print March 2, 2017.

Address for reprints: Eric E. Roselli, MD, Heart and Vascular Institute, Department of Thoracic and Cardiovascular Surgery, Cleveland Clinic, 9500 Euclid Ave/Desk J4-1, Cleveland, OH 44195 (E-mail: roselle@ccf.org).

0022-5223/\$36.00

Copyright © 2017 Published by Elsevier Inc. on behalf of The American Association for Thoracic Surgery

<http://dx.doi.org/10.1016/j.jtcvs.2017.01.006>

Recent studies demonstrate that a small but important minority of patients presenting with aortic root pathology have concomitant mitral valve (MV) dysfunction (7%),

Scanning this QR code will take you to a supplemental video and figure for the article.

Abbreviations and Acronyms

CT	= computed tomography
MR	= mitral regurgitation
MV	= mitral valve
VPRR	= valve-preserving root reimplantation

and recognition of this association is increasingly common.¹⁻³ This combination of pathologies is particularly common in patients with connective tissue disorders, such as Marfan syndrome and Loeys–Dietz syndrome.^{2,4-6} In addition, patients presenting with MV pathology occasionally have concomitant aortic root dilatation that is incidentally discovered during their preoperative workup, which often includes computed tomography (CT). Aortic valve-preserving root reimplantation (VPRR), replacement of the aortic root with valved conduits or allografts, and MV repair or replacement are established surgical options to treat these common valve and aortic root pathologies. However, the combination of an MV operation with an aortic root procedure is more demanding than either operation alone,⁷ and knowledge regarding clinical outcomes is limited.^{1,3,8-11} This study sought to characterize the pathology, surgical outcomes, long-term survival, and valve durability of patients undergoing combined primary aortic root and MV operations.

MATERIALS AND METHODS

Patients

A total of 360 adult patients underwent primary combined aortic root and MV surgery between January 1987 and January 2016 at the Cleveland Clinic. Patients with aortic stenosis, endocarditis, rheumatic MV disease, and reoperations were excluded to focus on patients who might be candidates for combined repair. A total of 118 patients met the inclusion criteria. Use of these data for research was approved by the Cleveland Clinic Institutional Review Board, with patient consent waived. Preoperative patient characteristics are summarized in [Table 1](#).

Echocardiography

All patients underwent a comprehensive echocardiogram, using commercially available instruments as part of standard clinical diagnostic evaluation. Cardiac measurements were obtained according to recommendations,^{12,13} and left ventricular ejection fraction was calculated using Simpson's biplane method. Diastolic function was graded using standard techniques.¹⁴ Diagnosis of bicuspid aortic valve was based on multiple views made during systole, demonstrating 2 aortic valve cusps; a raphe was noted when present.¹³ Annuloaortic ectasia was identified when the diameter of the aortic annulus was increased out of proportion to the size of the aortic leaflets.¹⁵ A semiquantitative scale of 0 to 4 (trace, mild, moderate, moderate to severe, and severe) was used to stratify valvular regurgitation on the basis of spectral and color Doppler, left atrial size, and width of the regurgitant jet.¹⁶

Cross-Sectional Imaging Measurements

Preoperative cross-sectional imaging was available in 68 patients (58%). Detailed imaging analyses were made from CT and magnetic

resonance imaging using 3-dimensional reconstruction software (TeraRecon, Foster City, Calif). Aortic cross-sectional diameters were collected in the orthonormal plane to the centerline of the aorta at 4 different landmarks based on the American College of Cardiology/American Heart Association consensus guidelines¹⁷ and the technique of Mendoza and colleagues.¹⁸

Surgical Details

The decision to perform combined MV and aortic root procedures was made by the cardiologist and cardiothoracic surgeon at the time of original clinical evaluation. In adhering to the guidelines,^{17,19} we offer early prophylactic aortic replacement at an ascending or sinus diameter 5.0 cm or greater, cross-sectional area to height ratio greater than 10 cm²/m, or the rate of increase in aortic dilation is 0.5 cm or greater per year in patients with bicuspid aortic valve aortopathy. If patients with bicuspid valves and associated aortic root enlargement have indications for aortic valve replacement because of severe aortic stenosis or aortic regurgitation, it is recommended that repair of the aortic root or replacement of the ascending aorta be performed if the diameter of these structures is greater than 4.5 cm. Surgery is indicated at lower size thresholds in patients with certain genetic syndromes, including a threshold of 4.5 to 5.0 cm for Marfan syndrome and 4.2 cm for Loeys–Dietz syndrome or a confirmed TGFBR1 or TGFBR2 mutation. In the absence of a bicuspid valve or genetic/familial cause of aortic enlargement, the threshold recommended for elective surgery at our center is an aortic diameter of 5.5 cm for patients with degenerative thoracic aneurysms, chronic aortic dissections, penetrating atherosclerotic ulcers, mycotic aneurysms, or pseudoaneurysms.

Posterior MV leaflet repair was achieved by triangular/quadrangular resection, folding valvuloplasty, and sliding repair. Anterior MV leaflet repair was achieved by chordal transfer or insertion of polytetrafluoroethylene neochordae. MV repair was achieved in 102 patients (86%) and included a combination of annuloplasty and chordal/leaflet procedures in 63 patients (62%), annuloplasty alone in 34 patients (33%), and chordal/leaflet procedures alone in 5 patients (5%). Six patients (5%) underwent bioprosthetic MV replacement, and 10 patients (9%) underwent mechanical MV replacement. The aortic root operative techniques have been described, including a modified valve reimplantation by Svensson and colleagues,^{1,20} composite mechanical valve implantation,^{21,22} standard techniques for biologic implants with coronary buttons, and allograft root implantation by the inclusion or button technique. Homograft root replacement was more common earlier in the series. At that time, there was a general belief (since disproved) that homografts had greater durability than other bioprostheses.²³ Today, we are less likely to use a homograft in a patient who does not have endocarditis. Aortic root/valve procedures included valve-preserving reimplantation in 43 patients (36%), Bentall procedure in 55 patients (bio-Bentall 29, mechanical-Bentall 26; 47%), and homograft in 20 patients (17%) ([Table 2](#)).

Forty-three patients (36%) received concomitant extended ascending aorta replacement, 19 patients (16%) underwent coronary artery bypass graft surgery, 5 patients (4%) underwent patent foramen ovale/atrial septal defect closure, 14 patients (12%) received an ablation for atrial fibrillation, and 12 patients (10%) underwent tricuspid valve repair. A video demonstrating one of these combined mitral valve repair and valve-preserving aortic root reimplantation procedures is included with this article ([Video 1](#)).

End Points

The primary end point was time-related mortality from the date of operation to death or last follow-up. Secondary end points included in-hospital mortality, and complications as defined by the Society of Thoracic Surgeons

TABLE 1. Baseline clinical and imaging characteristics of the patients

Variable	No. of available patients	No. (%) or mean $\pm$ SD
Demography		
Male	118	96 (81)
Age	118	52.40 $\pm$ 17.71
BMI (kg/m ²)	120	22.35 $\pm$ 3.89
Symptoms		
NYHA class	112	
I		42 (38)
II		48 (43)
III		19 (17)
IV		3 (2)
Comorbidities		
Hypertension	116	72 (61)
Diabetes	117	7 (6)
Myocardial infarction	118	10 (9)
Cerebrovascular accident	118	6 (5)
Congestive heart failure	118	25 (21)
COPD	116	15 (13)
Valve pathology		
Aortic valve pathology	118	
Normal tricuspid		27 (23)
Dysfunctional bicuspid		17 (14)
Annuloaortic ectasia		53 (45)
Degenerative calcification		21 (18)
MV cause	118	
Degenerative		92 (78)
Functional		26 (22)
MV pathology		
Isolated anterior leaflet	118	12 (10)
Prolapse	12	11 (92)
Calcification	12	1 (8)
Isolated posterior leaflet	118	30 (25)
Prolapse	30	25 (84)
Restricted opening	30	1 (3)
Calcification	30	4 (13)
Bileaflet	118	50 (43)
Anterior prolapse	50	49 (98)
Anterior restricted opening	50	1 (2)
Posterior prolapse	50	49 (98)
Posterior restricted opening	50	1 (2)
Isolated annular dilation	118	26 (22)
Aortic root pathology		
Degenerative aneurysm	118	111 (94)
Aortic dissection	118	5 (4)
Aneurysm + dissection	118	2 (2)
Echocardiography		
Aortic valve regurgitation	118	
0		16 (13)
1+		13 (11)
2+		24 (20)
3+		29 (25)
4+		36 (31)
MV regurgitation	118	
2+		15 (13)

(Continued)

TABLE 1. Continued

Variable	No. of available patients	No. (%) or mean $\pm$ SD
3+		44 (37)
4+		59 (50)
Left ventricular end-diastolic diameter, cm	94	6.0 $\pm$ 1.0
Left ventricular end-systolic diameter, cm	94	4.0 $\pm$ 1.0
Left ventricular ejection fraction (%)	116	53.4 $\pm$ 13
CT		
Sinus of Valsalva (mm)	65	46.6 $\pm$ 10
Sinotubular junction (mm)	51	43.2 $\pm$ 9.5
Tubular ascending (mm)	65	40.2 $\pm$ 11.2
Maximum ascending (mm)	66	40.5 $\pm$ 11.5

SD, Standard deviation; BMI, body mass index; NYHA, New York Heart Association; COPD, chronic obstructive pulmonary disease; CT, computed tomography; MV, mitral valve.

National Cardiac Database (http://www.sts.org/sites/default/files/documents/STSAAdultCVDDataSpecificationsV2_81.pdf), as well as time-related reoperation for MV or aortic root or valve disease. Patients were actively followed up at 2-year intervals after surgery by mailed institutional review board–approved questionnaire, telephone interview, or examination at Cleveland Clinic. The mortality follow-up information was supplemented by query of the Social Security Death Master File on October 27, 2011.

Data Analysis

Categorical variables are summarized as percentages, and continuous variables are presented as mean $\pm$ standard deviation. All measurements were performed by 1 observer, and intraobserver variability was determined by comparing measurements at individual landmarks taken by the same blinded observer in 10 randomly selected patients. Bland–Altman analysis was computed to assess measurement reproducibility. Time-to-event Kaplan–Meier analysis was performed for survival.

Competing Risk Analysis for Reoperation. Common interval was taken as the earliest of the outcome (death and any valve/root reoperation) or the interval between surgery and the end of follow-up for those patients still alive and having not experienced a reoperation. Time zero is time of surgery. Freedom from each event is estimated by the nonparametric product limit method of Andersen and colleagues.²⁴ Competing risk analyses were performed for the entire population, combined VPRR and MV repair group, and combined MV replacement and Bentall/Homograft procedure group.

All analyses were performed using SPSS (version 15.0.0; SPSS Inc, Chicago, Ill), MATLAB software (V7.8, R2009A, Natick, Mass), and SAS statistical software (SAS version 9.2; SAS Institute, Cary, NC).

RESULTS

Patient Characteristics

The most common preoperative presentations included degenerative MV disease (n = 92, 78%) and degenerative aortic root aneurysm (n = 111, 94%). Mean age of patients at operation was 52 $\pm$ 17.7 years, and 96 (81%) were male. At the time of presentation, all patients had mitral regurgitation (MR) 2+ or greater, and 102 patients (86%) had aortic regurgitation.

TABLE 2. Operative details and outcomes

Variable	No. (%) or mean $\pm$ SD*
Operative details	
MV repair	102 (86)
Anterior	24 (20)
Neochordae	3 (3)
Cleft closure	3 (3)
Chordae transfer	8 (7)
Patch repair	5 (4)
Posterior	62 (53)
Resection	45 (38)
Folding repair	5 (4)
Neochordae	1 (1)
Cleft closure	6 (5)
Sliding repair	8 (7)
Annular debridement	2 (2)
Isolated annuloplasty	34 (29)
Alfieri stitch	10 (9)
Commissuroplasty	6 (5)
MV replacement	16 (14)
Biologic valve	6 (5)
Mechanical valve	10 (9)
Aortic root procedure	
VPRR	43 (36)
Bio-Bentall	29 (25)
Mechanical-Bentall	20 (17)
Homograft	20 (17)
Porcine root bioprosthesis	6 (5)

SD, Standard deviation; MV, mitral valve; VPRR, valve-preserving root reimplantation. *Number of available patients = 118.

Twenty-seven patients (23%) had a normally functioning tricuspid aortic valve, 18 patients (15%) had bicuspid aortic valve disease, 29 patients (25%) had Marfan syndrome, and 5 patients (4%) had combined bicuspid aortic valve and Marfan syndrome. Substantial percentages of patients had

FIGURE 1. Trends in operative strategy: MV repair and valve-preserving aortic root procedure by calendar year in patients undergoing combined operations.

severe aortic regurgitation ($n = 36$, 31%) and severe MR ($n = 59$, 50%).

The most common MV pathology was bileaflet prolapse, present in 50 patients (43%). The most common MV procedures were mitral annuloplasty in 97 patients (82%) and posterior leaflet resection in 45 patients (38%). Although the most common type of aortic root surgery was a Bentall procedure ($n = 55$, 47%), the combination of valve-preserving reimplantation for the aortic root/valve and MV repair has increased in recent experience (Figure 1).

During the cross-sectional imaging analysis, the intraobserver variability was 3 mm at the aortic sinus, 5 mm at the sinotubular junction, and 6 mm at the ascending aorta (Figure E1). The mean maximum aortic diameter was 46.6 ± 10 mm and was most commonly at the level of the sinuses of Valsalva (Table 1).

VIDEO 1. Combined aortic root and MV surgery: the quest to preserve both valves. Video available at: [http://www.jtcvsonline.org/article/S0022-5223\(17\)30122-8/addons](http://www.jtcvsonline.org/article/S0022-5223(17)30122-8/addons).

FIGURE 2. Estimated survival: Kaplan-Meier curves show survival for patients undergoing combined MV and aortic root surgery (black line), VPRR and MV repair (green line), and Bentall/homograft and MV surgery (blue line). MV, Mitral valve; VPRR, valve-preserving root reimplantation.

In-Hospital Outcomes

Total cardiopulmonary bypass time was 163.97 ± 52.66 minutes, and total ischemic time was 128.46 ± 39.54 minutes. There were 2 (1.7%) in-hospital deaths. Three patients (2.5%) had stroke, 10 patients (8.5%) had prolonged ventilation, 3 patients (2.5%) had renal failure, 46 patients (35.4%) had new-onset postoperative atrial fibrillation, 2 patients (1.7%) had sepsis, and 12 patients (10.2%) required reexploration for bleeding.

Survival

Median follow-up time among survivors was 5.31 years (interquartile range, 1-12 years), with 20% followed for more than 13 years and 10% followed for more than 16 years. There was an 86% response rate to the 2-year follow-up questionnaire and a mean rate to all questionnaires of 70%, but only 1 patient was completely lost to follow-up.

Time-related survival of the patients after 1, 5, 10, and 15 years was 98%, 91%, 79%, and 71%, respectively. In patients who underwent combined VPRR and MV repair ($n = 41$, 35%), time-related survival after 1, 5, and 10 years was 97%, 97%, and 89%, respectively. Among patients with combined Bentall/homograft root replacement and MV surgery ($n = 75$, 64%), time-related survival after 1, 5, and 10 years was 97%, 88%, and 73%, respectively. [Figure 2](#) demonstrates the time-related survival of patients who underwent combined MV and aortic root procedures.

Competing Risk Analysis for Reoperation

Median active follow-up time for valve/root reoperation was 5 years (interquartile range, 0.57-11 years). Twenty percent of the patients were followed for more than 12 years, and 10% of the patients were followed for more than 14 years. From surgery to 2 years, the risk of reoperation exceeded the risk of death. In the later stages of follow-up, the

FIGURE 3. Competing risk analyses for reoperation in patients who underwent aortic root and MV procedures. The *red line* represents nonparametric estimates of the percentage of patients dying before reoperation; the *blue line* represents the percentage of patients undergoing reoperation; the *black line* represents the percentage of patients alive without reoperation. At any point in time, the sum of percentages of the 3 categories equals 100%. Symbols are nonparametric estimates, and vertical bars confidence limits equivalent to ± 1 standard error (68% confidence interval). A, Aortic root and MV surgery. B, Valve-preserving root replacement and MV repair. C, Bentall/homograft and MV replacement.

risk of death exceeds the risk of reoperation. At 1, 2, 5, and 10 years, the risk of reoperation was 4.7%, 4.7%, 4.7%, and 12% versus 2.6%, 3.8%, 7.7%, and 22% for death, respectively (Figure 3, A).

The modes of valvular failure were recurrent severe MR after MV repair ($n = 4$), endocarditis after mechanical valve replacement ($n = 1$), degenerated aortic homograft ($n = 4$), valve dysfunction after valve-preserving aortic root replacement ($n = 3$), and structural valve deterioration after Bentall procedure ($n = 2$).

Combined valve-preserving aortic root reimplantation and mitral valve repair. Before the first decade of follow-up, the risk of reoperation was greater than the risk of death. At 1, 2, 5, and 10 years, the risk of reoperation was 7.8%, 7.8%, 7.8%, and 7.8% versus 2.8%, 2.8%, 2.8%, and 21% for risk of death, respectively (Figure 3, B).

Bentall/homograft root replacement and mitral valve surgery. From surgery to end of follow-up, the risk of death was greater than the risk of reoperation. At 1, 2, 5, and 10 years, the risk of reoperation was 3.0%, 3.0%, 3.0%, and 9.8% versus 3.0%, 4.4%, 9.8%, and 24% for risk of death, respectively (Figure 3, C).

DISCUSSION

Key Findings

The coexistence of aortic root and MV pathology is increasingly recognized among surgical patients. Patients undergoing primary combined aortic root and MV surgery are young. The most common pathologies are root aneurysm without dissection and degenerative MV disease. Combined aortic root and MV operations are safe in centers with expertise in both procedures and are associated with excellent long-term survival and durability. Our recent experience confirms that preservation of both valves provides excellent outcomes and durability through the first decade.

Surgical Approaches and Outcomes

The benefits of MV repair versus replacement for patients with degenerative MV disease are well documented.²⁵⁻²⁷ Likewise, valve-preserving aortic root reimplantation is preferred for patients with aortic root aneurysm and a salvageable aortic valve.²⁸ Advantages include low surgical risk, potential for late durability, improved postoperative ventricular remodeling, avoidance of anticoagulation and its related complications, and no need for lifestyle limitations. In our relatively large cohort, operative mortality of 1.7% was lower than in other smaller series and is similar to that for the general population of patients undergoing isolated MV or aortic

root operation.^{1,2,29-31} We recommend that combined preservation of both valves for degenerative disease, when possible, is preferred as long as the safety is not compromised, as is often the case in experienced centers. In our center, this frequently involves the collaboration of 2 surgeons, 1 with special expertise in the management of aortic root pathology and 1 with extensive experience in MV repair.

The performance of valve-preserving aortic root replacement in the setting of aortic dissection is controversial. The safe use of valve-preserving aortic root replacement has been described for selected patients with acute ascending aortic dissection.³²⁻³⁴ As we have gained experience and comfort performing this operation in our institution, we have applied it to selected younger patients but have not yet combined it with mitral repair for this indication. In the current series, 7 patients (6%) had aortic root dissection with moderate to severe aortic regurgitation and mitral disease. They underwent MV repair and bio-Bentall root replacement. They tended to be aged more than 70 years and had some evidence of degeneration of the aortic valve cusps. The strategy of aortic root replacement combined with mitral repair in these patients produced good results.

Although consensus exists concerning early intervention for severe degenerative MR,^{35,36} the approach to the patient with moderate degenerative MR undergoing aortic root intervention is unclear.³⁷ The goal of therapy for both severe MR and aortic root aneurysm typically is a prophylactic operation meant to prolong life. Many of these patients are asymptomatic. Not surprisingly, a significant number of them are referred to surgery for one of the primary lesions and are incidentally found to have the other during the preoperative workup. Because we approach most MV disease with a minimally invasive first mindset, patients receive CT imaging of the chest in addition to echocardiography as a routine part of the workup. Likewise, because an understanding of aortic valve function is critical to the decision-making process for aortic root surgery, the patients who present with aortic root disease as the primary indication receive echocardiography in addition to CT. It has been shown that unaddressed MR after aortic valve surgery is associated with increased risks of long-term mortality and heart failure.^{38,39} In the current study, 59 patients (50%) underwent an MV procedure with less than severe MR ($>1+$ and $<4+$), but many of them had signs of advanced findings, including redundant leaflet tissue and a dilated annulus consistent with Barlow's disease. Among this subset of patients, 52 (88%) had MV repair and 7 (12%) had MV replacement; replacements tended to occur earlier in the series and

were often in patients with mitral annular calcification. It has been suggested that adding MV surgery to an aortic root/valve procedure increases the risk of mortality by 2-fold, but we did not find that to be the case.⁴⁰ There were no operative deaths and no late mitral reoperations in the subset of patients with moderate mitral disease, suggesting that proactive treatment of moderate MR is a safe and reasonable choice in patients undergoing a concomitant root procedure. Only 2 of these patients had more than mild MR 10 years after MV repair. A larger study with longer follow-up will be necessary to determine late clinical benefits associated with a MV procedure for moderate MR in patients undergoing aortic root operation.

In follow-up, 6 patients required MV reoperation and 12 patients required aortic root or valve reoperation. In a recent study by David and colleagues,² the freedom from reoperation for combined aortic root and MV procedure was 86% at 10 years, similar to that seen in our cohort; however, their population was different than ours and included patients with endocarditis.

Study Limitations

Inclusion in this study extended over a long period of time during which techniques evolved for treating both the aortic root and MVs, influencing the type of procedure chosen. As a retrospective study, the usual issues inherent to such a strategy limit it. Fourteen patients (14%) were lost to follow-up at different time points before 2-year active follow-up in the whole cohort, and 59% of combined VPRR and MV repair procedures were performed in the last 5 years, resulting in shorter follow-up for this subgroup. Furthermore, we did not have enough follow-up echocardiographic data to report the longitudinal recurrence of MR or AR as completely as that for survival. The study was not designed to compare repair and replacement procedures; however, as we gain more experience with a larger population of patients, we may be able to tease out the advantages of one strategy over another.

Despite the limited numbers of patients with documented connective tissue disorders, this population is relatively young, and it is likely that they have a common and possibly genetically triggered cause for degeneration of both the aorta and the MV. Patients with Marfan syndrome have a higher incidence of MR than the normal population.^{4,41} It is plausible that there may be a unique genetic abnormality in a proportion of these patients who present with both degenerative MR and aortic root dilatation but without other phenotypical features. We have now begun to refer these patients for evaluation with a cardiovascular geneticist and offer them genetic analysis.

CONCLUSIONS

In a high-volume center with dedicated aorta and MV specialists, treatment of combined aortic root pathology and MV disease can be achieved with low operative mortality. Preservation of both valves is often feasible and affords excellent durability.

Conflict of Interest Statement

E.E.R.: serves as a consultant and investigator for Medtronic, Cryolife, and LivaNova and as a speaker and investigator for Edwards Lifesciences, St Jude Medical, and Vascutek. R.M.S.: institutional research agreements with LivaNova, St Jude, Edwards, and Abbott. L.G.S.: Cardiosolutions stock and Posthorax royalty. A.M.G.: consultant to AtriCure, Medtronic, St Jude Medical, Edwards Lifesciences, Abbott Vascular, ClearFlow, and Cryolife; research support from St Jude Medical. All other authors have nothing to disclose with regard to commercial support.

References

1. Svensson LG, Batizy LH, Blackstone EH, Gillinov AM, Moon MC, D'Agostino RS, et al. Results of matching valve and root repair to aortic valve and root pathology. *J Thorac Cardiovasc Surg.* 2011;142:1491-8.e1497.
2. David TE, Armstrong S, Maganti M, Ihlberg L. Clinical outcomes of combined aortic root replacement with mitral valve surgery. *J Thorac Cardiovasc Surg.* 2008;136:82-7.
3. Svensson LG, Pillai ST, Rajeswaran J, Desai MY, Griffin B, Grimm R, et al. Long-term survival, valve durability, and reoperation for 4 aortic root procedures combined with ascending aorta replacement. *J Thorac Cardiovasc Surg.* 2016;151:764-74.e764.
4. Svensson L, Crawford E, Coselli J, Safi H, Hess K. Impact of cardiovascular operation on survival in the Marfan patient. *Circulation.* 1989;80:1233-42.
5. Svensson LG, Blackstone EH, Alsalihi M, Batizy LH, Roselli EE, McCullough R, et al. Midterm results of David reimplantation in patients with connective tissue disorder. *Ann Thorac Surg.* 2013;95:555-62.
6. Kunkala MR, Schaff HV, Li Z, Volguina I, Dietz HC, LeMaire SA, et al. Mitral valve disease in patients with Marfan syndrome undergoing aortic root replacement. *Circulation.* 2013;128:S243-7.
7. Idrees JJ, Roselli EE, Lowry AM, Reside JM, Javadikasgari H, Johnson DJ, et al. Outcomes after elective proximal aortic replacement: a matched comparison of isolated versus multicomponent operations. *Ann Thorac Surg.* 2016;101:2185-92.
8. Svensson LG, Blackstone EH, Feng J, de Oliveira D, Gillinov AM, Thamilarasan M, et al. Are Marfan syndrome and marfanoid patients distinguishable on long-term follow-up? *Ann Thorac Surg.* 2007;83:1067-74.
9. Gillinov AM, Blackstone EH, White J, Howard M, Ahkrass R, Marullo A, et al. Durability of combined aortic and mitral valve repair. *Ann Thorac Surg.* 2001;72:20-7.
10. Gott VL, Cameron DE, Alejo DE, Greene PS, Shake JG, Caparrelli DJ, et al. Aortic root replacement in 271 Marfan patients: a 24-year experience. *Ann Thorac Surg.* 2002;73:438-43.
11. Zehr KJ, Orszulak TA, Mullany CJ, Matloobi A, Daly RC, Dearani JA, et al. Surgery for aneurysms of the aortic root a 30-year experience. *Circulation.* 2004;110:1364-71.
12. Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. *J Am Soc Echocardiogr.* 2005;18:1440-63.

13. Baumgartner H, Hung J, Bermejo J, Chambers JB, Evangelista A, Griffin BP, et al. Echocardiographic assessment of valve stenosis: EAE/ASE recommendations for clinical practice. *Eur J Echocardiogr*. 2009;10:1-25.
14. Nagueh SF, Appleton CP, Gillebert TC, Marino PN, Oh JK, Smiseth OA, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. *J Am Soc Echocardiogr*. 2009;22:107-33.
15. David TE, Feindel CM, Bos J. Repair of the aortic valve in patients with aortic insufficiency and aortic root aneurysm. *J Thorac Cardiovasc Surg*. 1995;109:345-52.
16. Zoghbi WA, Enriquez-Sarano M, Foster E, Grayburn PA, Kraft CD, Levine RA, et al. Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional and Doppler echocardiography. *J Am Soc Echocardiogr*. 2003;16:777-802.
17. Hiratzka LF, Bakris GL, Beckman JA, Bersin RM, Carr VF, Casey DE, et al. 2010 ACCF/AHA/AATS/ACR/ASA/SCA/SCAI/SIR/STS/SVM guidelines for the diagnosis and management of patients with thoracic aortic disease. *J Am Coll Cardiol*. 2010;55:e27-129.
18. Mendoza DD, Kochar M, Devereux RB, Basson CT, Min JK, Holmes K, et al. Impact of image analysis methodology on diagnostic and surgical classification of patients with thoracic aortic aneurysms. *Ann Thorac Surg*. 2011;92:904-12.
19. Svensson LG, Adams DH, Bonow RO, Kouchoukos NT, Miller DC, O'Gara PT, et al. Aortic valve and ascending aorta guidelines for management and quality measures: executive summary. *Ann Thorac Surg*. 2013;95:1491-505.
20. Svensson LG. Sizing for modified David's reimplantation procedure. *Ann Thorac Surg*. 2003;76:1751-3.
21. Nakahira A, Shibata T, Sasaki Y, Hirai H, Hattori K, Hosono M, et al. Outcome after the modified Bentall technique with a long interposed graft to the left coronary artery. *Ann Thorac Surg*. 2009;87:109-15.
22. Svensson LG. Approach for insertion of aortic composite valve grafts. *Ann Thorac Surg*. 1992;54:376-8.
23. Smedira NG, Blackstone EH, Roselli EE, Laffey CC, Cosgrove DM. Are allografts the biologic valve of choice for aortic valve replacement in nonelderly patients? Comparison of explantation for structural valve deterioration of allograft and pericardial prostheses. *J Thorac Cardiovasc Surg*. 2006;131:558-64.e554.
24. Andersen PK, Borgan Ø, Gill RD, Keiding N. *Nonparametric Estimation. Statistical Models Based on Counting Processes*. New York: Springer; 1993: 176-331.
25. Gillinov AM, Blackstone EH, Nowicki ER, Slisatkov W, Al-Dossari G, Johnston DR, et al. Valve repair versus valve replacement for degenerative mitral valve disease. *J Thorac Cardiovasc Surg*. 2008;135:885-93.e882.
26. Mick SL, Keshavamurthy S, Gillinov AM. Mitral valve repair versus replacement. *Ann Cardiothorac Surg*. 2015;4:230-7.
27. Gillinov AM, Blackstone EH, Alaulaqi A, Sabik JF, Mihaljevic T, Svensson LG, et al. Outcomes after repair of the anterior mitral leaflet for degenerative disease. *Ann Thorac Surg*. 2008;86:708-17.
28. Price J, Svensson LG. Indications for repair of the aneurysmal aorta. *Semin Thorac Cardiovasc Surg*. 2013;24:261-6.
29. Woldendorp K, Starra E, Seco M, Hendel PN, Jeremy RW, Wilson MK, et al. Replacement of the aortic root with a composite valve-graft conduit: risk factor analysis in 246 consecutive patients. *Heart Lung Circ*. 2014;23:1187-93.
30. Caceres M, Ma Y, Rankin JS, Saha-Chaudhuri P, Englum BR, Gammie JS, et al. Mortality characteristics of aortic root surgery in North America. *Eur J Cardiothorac Surg*. 2014;ezu083.
31. Rankin JS, He X, O'Brien SM, Jacobs JP, Welke KF, Filardo G, et al. The Society of Thoracic Surgeons risk model for operative mortality after multiple valve surgery. *Ann Thorac Surg*. 2013;95:1484-90.
32. David TE, Feindel CM, Webb GD, Colman JM, Armstrong S, Maganti M. Long-term results of aortic valve-sparing operations for aortic root aneurysm. *J Thorac Cardiovasc Surg*. 2006;132:347-54.
33. Subramanian S, Leontyev S, Borger MA, Trommer C, Misfeld M, Mohr FW. Valve-sparing root reconstruction does not compromise survival in acute type A aortic dissection. *Ann Thorac Surg*. 2012;94:1230-4.
34. Valo J, Jokinen JJ, Kaarne M, Ihlberg L. Expanding indications for valve-sparing aortic root reconstruction: early and midterm results. *Ann Thorac Surg*. 2013;95:579-85.
35. Nishimura RA, Otto CM, Bonow RO, Carabello BA, Erwin JP, Guyton RA, et al. 2014 AHA/ACC guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol*. 2014;63:e57-185.
36. Suri RM, Schaff HV, Enriquez-Sarano M. Mitral valve repair in asymptomatic patients with severe mitral regurgitation: pushing past the tipping point. *Semin Thorac Cardiovasc Surg*. 2014;26:95-101.
37. McCarthy FH, Desai ND, Fox Z, George J, Moeller P, Vallabhajosyula P, et al. Moderate mitral regurgitation in aortic root replacement surgery: comparing mitral repair with no mitral repair. *J Thorac Cardiovasc Surg*. 2014;147:938-41.
38. Harris KM, Sundt TM III, Aeppli D, Sharma R, Barzilai B. Can late survival of patients with moderate ischemic mitral regurgitation be impacted by intervention on the valve? *Ann Thorac Surg*. 2002;74:1468-75.
39. Barreiro CJ, Patel ND, Fitton TP, Williams JA, Bonde PN, Chan V, et al. Aortic valve replacement and concomitant mitral valve regurgitation in the elderly impact on survival and functional outcome. *Circulation*. 2005;112:1443-7.
40. Litmathe J, Boeken U, Kurt M, Feindt P, Gams E. Predictive risk factors in double-valve replacement (AVR and MVR) compared to isolated aortic valve replacement. *Thorac Cardiovasc Surg*. 2006;54:459-63.
41. Bhudia SK, Troughton R, Lam BK, Rajeswaran J, Mills WR, Gillinov AM, et al. Mitral valve surgery in the adult Marfan syndrome patient. *Ann Thorac Surg*. 2006;81:843-8.

Key Words: aortic root replacement, aortic regurgitation, aortic aneurysm, mitral regurgitation, mitral valve surgery

FIGURE E1. Bland–Altman Plot for intraobserver variability for 10 random CT scan measurements. A, Aortic sinus. B, Sinotubular junction. C, Ascending tubular. D, Maximum ascending. All intraobserver differences with 95% confidence interval. *SD*, Standard deviation.