Results of matching valve and root repair to aortic valve and root pathology

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Objective: For patients with aortic root pathology and aortic valve regurgitation, aortic valve replacement is problematic because no durable bioprosthesis exists, and mechanical valves require lifetime anticoagulation. This study sought to assess outcomes of combined aortic valve and root repair, including comparison with matched bioprosthesis aortic valve replacement.

Methods: From November 1990 to January 2005, 366 patients underwent modified David reimplantation (n = 72), root remodeling (n = 72), or valve repair with sinotubular junction tailoring (n = 222). Active follow-up was 99% complete, with a mean of 5.6 ± 4.0 years (maximum 17 years); follow-up for vital status averaged 8.5 ± 3.6 years (maximum 19 years). Propensity-adjusted models were developed for fair comparison of outcomes.

Results: Thirty-day and 5-, 10-, and 15-year survivals were 98%, 86%, 74%, and 58%, respectively, similar to that of the US matched population and better than that after bioprosthesis aortic valve replacement. Propensity-score–adjusted survival was similar across procedures ($P > .3$). Freedom from reoperation at 30 days and 5 and 10 years was 99%, 92%, and 89%, respectively, and was similar across procedures ($P > .3$) after propensity-score adjustment. Patients with tricuspid aortic valves were more likely to be free of reoperation than those with bicuspid valves at 10 years (93% vs 77%, $P = .002$), equivalent to bioprosthesis aortic valve replacement and superior after 12 years. Bioprostheses increasingly deteriorated after 7 years, and hazard functions for reoperation crossed at 7 years.

Conclusions: Valve preservation (rather than replacement) and matching root procedures have excellent early and long-term results, with increasing survival benefit at 7 years and fewer reoperations by 12 years. We recommend this procedure for experienced surgical teams. (J Thorac Cardiovasc Surg 2011;142:1491-8)

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For patients with aortic root disease and aortic valve regurgitation, management of the aortic valve is problematic because patients present in a similar manner from diverse disease pathologies that require tailored operative procedures. Although valve replacement is common in such patients, there is no ideal prosthesis in this circumstance. No durable bioprosthetic valve replacement device is available.[1-3] Porcine and pericardial valves carry risks of endocarditis, stroke, and early structural valve failure, particularly in younger patients, and allografts have no better durability than bovine pericardial valves when patient age is taken into account.[1] Although the Ross procedure is a reasonable alternative in patients aged less than approximately 30 years, durability of both the aortic autograft and the pulmonary allograft is limited.[1] Aortic valve replacement (AVR) with a mechanical valve carries the risks of anticoagulation-related hemorrhage, thrombosis, embolization, stroke, endocarditis, and greater blood turbulence, as seen with high-intensity transient signals.[1,2,4-7] Zellner and colleagues[7] report event-free survival of 40% at 10 years for mechanical valves. In addition, in patients undergoing AVR and root and ascending AVR with composite

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Abbreviations and Acronyms
AVR = aortic valve replacement
IRB = institutional review board

mechanical valve grafts, 10-year survival is only 60% and 10-year event-free survival 40%.[1,2]

Because of these problems, there has been increased emphasis in young patients on trying to repair the aortic valve and root to avoid valve replacement. Three approaches have been described for preserving the aortic valve while repairing the aortic root: (1) root remodeling operations (David or Yacoub procedure)[3,8-14]; (2) aortic valve reimplantation using various iterations of the David procedure[3,4,8,10,12,15-20]; and (3) aortic sinotubular junction reduction and tailoring procedures, frequently combined with aortic cusp repair.[1,11,12,21-24] We refer to all 3 as valve-preserving operations.

The objective of this study was to compare outcomes, particularly long-term survival and risk of reoperation, after these 3 types of valve-preserving procedures for aortic root disease accompanied by aortic valve regurgitation.

PATIENTS AND METHODS

Patients

From November 1990 to January 2005, 366 consecutive patients underwent aortic valve-preserving operations for aortic root disease, excluding aortic valve stenosis—46 at Lahey Clinic (LGS) and 320 at Cleveland Clinic. Of these, 72 underwent a modified David reimplantation procedure, 72 underwent aortic root remodeling, and 222 underwent aortic valve repair with sinotubular junction tailoring. Data were collected prospectively on all patients, supplemented by medical record review as required, and entered into a database. Data were then collated for analysis (Table E1). Use of these data for research was approved by the institutional review boards (IRBs) of both institutions, with patient consent waived.

Surgical Techniques

The surgical techniques, including selection of appropriate approach for the underlying pathology, have been described extensively by us and others.[1-5,8-25] Aortic arch replacement was performed only for important dilatation or aortic dissection. Briefly, for degenerative aneurysms, our surgical preference was a modified David reimplantation operation for patients with a teardrop-shaped deformity (Erdheim deformity).[16,17] For most patients with bicuspid aortic valves, we used cusp repairs combined with aortic root remodeling or sinotubular junction tailoring.[11,22] If valve regurgitation appeared to be predominantly related to splaying of the commissures at the sinotubular junction caused by dilatation, the preferred procedure was sinotubular junction tailoring and reduction, with or without aortic cusp or root repair.[21] Aortic cusp repair procedures included narrowing the intercommissural angle by Cabrol sutures, repairing perforations, plicating or resecting excess cusp tissue, placing figure-of-8 supracommissural cusp sutures, and debriding excess tissue.

Patients who had only aortic valve and commissure resuspension during repair of aortic dissections were excluded from this study. For the first 30 days after surgery, patients who underwent root-preserving procedures were placed on a 75-mg daily dose of clopidogrel and thereafter encouraged to take an aspirin daily. Prophylactic antibiotics for any invasive procedure, blood pressure control, and use of beta-blockers were also strongly advised.

End Points

Primary end points were (1) all-cause mortality, including in-hospital deaths, and (2) aortic valve reoperation. For survival reference, age-, sex-, and race-matched estimates of survival in the US population were calculated. Similarly, a curve was derived for survival after AVR with a bovine pericardial device (Perimount; Carpentier-Edwards, Irvine, Calif) based on age, sex, New York Heart Association functional class, and concomitant coronary artery bypass grafting using premarket approval data.[26] For reoperation reference, age-matched freedom from reoperation for structural valve degeneration was calculated also from premarket approval data for bovine pericardial aortic valve prostheses.[26]

Follow-up

Patients were mailed a letter to obtain permission for an interview and then contacted by a mailed IRB-approved questionnaire or directly by telephone using an IRB-approved script at 2, 5, 10, and 15 years after surgery. Mean follow-up was 5.6 ± 4.0 years (maximum 17 years); 2010 patient-years of data were available for analysis. Follow-up was 99% complete (all but 1 patient). Among survivors, 10% were followed actively more than 11 years. For survival, active anniversary follow-up was supplemented by passive mortality data from the Social Security Death Master File, post-dated to March 13, 2010. Thus, for survival, mean follow-up was 8.5 ± 3.6 years (maximum 19 years), and 2790 patient-years of data were available for analysis.

Data Analysis

Study design for fair comparison of outcomes. Because aortic root techniques were not assigned randomly to each patient, direct comparison of end points is confounded by selection factors. Therefore, we approached the analysis from the perspective of study design rather than outcome analysis.[27] From this perspective, we attempted to approximate a randomized trial and characterize treatment effects for the groups (rather than seeking risk factors for outcomes) by identifying treatment allocation factors. For example, patients undergoing reimplantation or remodeling were younger than those undergoing tailoring, and patients undergoing reimplantation were less likely to undergo emergency operation than were patients undergoing tailoring (Table E1). Patients undergoing reimplantation also were taller and had a larger body surface area than patients undergoing tailoring, in keeping with our preference for this operation in patients with Marfan syndrome. Formal identification of treatment allocation was accomplished by a form of logistic regression analysis that simultaneously identified factors associated with each of the 3 procedure groups (polytomous logistic regression). Initially, a model that included only factors found to be statistically significantly associated with at least one of the procedures was developed using variables in Table E2 (parsimonious model, Table E3) to describe the nature of treatment decisions. This was amplified into a propensity model (Table E4) by adding factors from each class of variables regardless of statistical significance.[28,29] From this model, propensity scores for each type of procedure were calculated for each patient. These were incorporated into multivariable analyses of end points, which, in essence, adjusts the estimates of treatment effect for selection bias.[30]

Unadjusted time-related estimates. Estimates of unadjusted overall and stratified survival and freedom from reoperation were obtained nonparametrically using the Kaplan–Meier method. Estimates were also obtained by a completely parametric method that automatically decomposes time-varying risk (eg, early elevated risk of death after an operation) into simple components called phases, each of which can be independently modulated by risk factors, much like mixing primary colors to create a resulting color.[31] (For additional details, see http://www.clevelandclinic.org/heartcenter/hazard.)

Risk-adjusted time-related estimates. Multivariable analyses for death and reoperation were performed using the multiphase parametric hazard model described in the preceding text. Variable selection used bagging[32] and the list of candidate risk factors in Table E2. This involved automated stepwise analysis of 1000 resampled (bootstrap) data sets. This was followed by tabulating the frequency of occurrence at $P \leq .05$ of both single factors and closely related clusters of factors (eg, transformations of scale of a single variable to select the one most linear with respect to outcome, or closely related variables, such as different expressions of patient size). Variables present in 50% or more of the models were retained (median rule). Finally, the procedure variables and propensity scores for more comprehensive risk-adjustment were forced into the models to evaluate whether procedure type was associated with these time-related outcomes.

Presentation. Continuous variables are summarized by mean ± standard deviation unless distributions were skewed, in which case median and (for consistency) 15th and 85th percentiles are given. Regression coefficients are accompanied by ±1 standard error. For consistency, time-related estimates are accompanied by 68% confidence limits equivalent to ±1 standard error. Categoric variables are summarized by frequency and percentage.

RESULTS

Survival

Unadjusted survivals, including in-hospital deaths, were 98%, 93%, 86%, 74%, and 58%, at 30 days and 1, 5, 10, and 15 years, respectively (Figure E1). The hazard function had 2 phases: an early rapidly declining phase in the immediate postoperative period followed by a late slowly rising phase (Figure E2). For informal reference, after the early high-risk phase, survival was similar to that of the age-, sex-, and race-matched US population; survival for the first 5 years was also similar to that after AVR with a bioprosthesis, and somewhat better thereafter. There were no 30-day or in-hospital deaths after modified David reimplantation of the aortic valve (Table 1).

Patients who were older, had longer aortic clamp time, or received an elephant trunk graft were at higher risk of early death (Table E5). Early survival declined more rapidly when aortic clamp time exceeded 90 minutes (Figure E3). Unadjusted stratified survival was highest after remodeling and reimplantation procedures (both 87% at 10 years) and lowest after sinotubular junction tailoring (66% at 10 years; Figure 1). However, differences in patient profile among these groups accounted for the disparity ($P \geq .3$; Table E5). For reference, Figure 1 also shows age-, sex-, and race-matched survival for the general US population and survival of matched patients after biologic AVR. Note the better survival with reimplantation and remodeling compared with both US survival and matched bioprosthesis survival.

Late survival was lower in older patients and in those undergoing operation earlier in the series (Table E5). Underlying pathology also influenced survival: Marfan syndrome, 100% survival at 10 years; bicuspid valve, 93% survival at 10 years; aortic dissection, 60% survival at 10 years; and degenerative aneurysm, 71% survival at 10 years (Figure 2). Four patients were known to have died late from aortic pathology, although the mode of death could not be determined for most deaths (Table E6).

Reoperation

There were 28 aortic valve reoperations. Overall unadjusted freedom from reoperation was 99%, 97%, 92%, and 89% at 30 days and 1, 5, and 10 years, respectively (Figure E4). Risk was highest in the first 18 months, but at 7 years, risk of reoperation for matched bioprostheses crossed the repair hazard function curve (Figure E5). Freedom from reoperation at 10 years was 85% after remodeling, 86% after reimplantation, and 91% after sinotubular junction tailoring, with no statistically significant difference among procedures ($P > .4$; Figure 3).

For reference, Figure 3 also shows age-matched reoperation for structural valve deterioration for bovine pericardial aortic valve bioprostheses. Procedures performed in patients with tricuspid aortic valves were associated with lower risk of reoperation than for those with a bicuspid valve ($P = .002$; Table 2, Figure 4). Indeed, at 7 years, when bioprostheses increasingly started to fail, the advantage was approximately 2% over repairs, and at 11 years

TABLE 1. In-hospital outcomes

	Reimplantation (total n = 72)		Remodeling (total n = 72)		Tailoring (total n = 222)		
Variable	n*	No. (%)	n*	No. (%)	n*	No. (%)	*P*
Hospital death	63	0 (0)	56	0 (0)	199	9 (4.5)	.07†
Postoperative MI	70	2 (2.9)	71	0 (0)	216	3 (1.4)	.4†
Blood product use‡							
RBCs	63	19 (30)	56	19 (34)	199	103 (52)	.002
Platelets	63	10 (16)	56	13 (23)	199	71 (36)	.006
FFP	63	6 (9.5)	56	6 (11)	199	54 (27)	.001
Stroke after operation	72	0 (0)	72	2 (2.8)	222	16 (7.1)	.02†
Permanent	72	0 (0)	72	0 (0)	222	4 (1.8)	.5†
Operative length of stay (d)	62	6 (5–10)§	56	6 (5–10)§	199	8 (5–21)§	<.0001

FFP, Fresh-frozen plasma; *MI*, myocardial infarction; *RBC*, red blood cell. *Patients with data available. †Fisher's exact test. ‡No. refers to number of patients who received blood or blood products, and in parentheses the percentage who received blood or blood products. Thus, 30% of patients undergoing reimplantation and for whom data were available received an RBC transfusion. §Median and 15th and 85th percentiles.

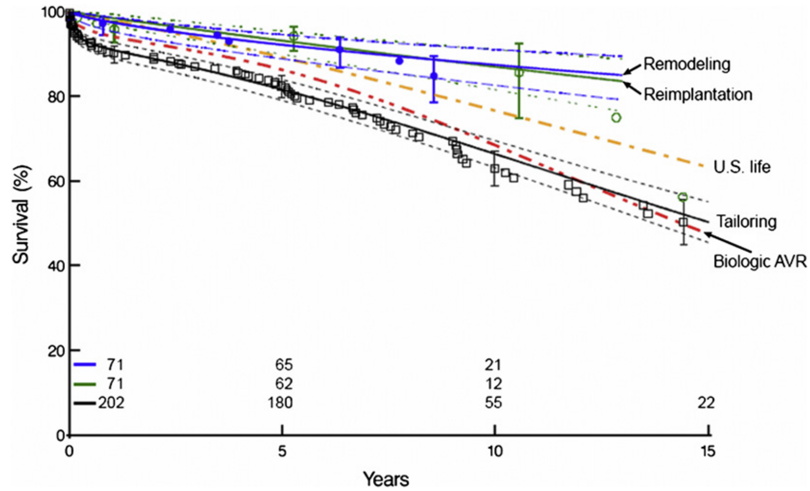

FIGURE 1. Unadjusted survival stratified by operative procedure. Each symbol represents a death, vertical bars represent asymmetric 68% confidence limits (CL) equivalent to ±1 standard error, and numbers in parentheses represent patients remaining at risk. *Solid lines* are independently derived parametric survival estimates enclosed within dashed 68% CLs. Patients remaining at risk appear at the bottom of the figure. For reference, the *dot-dash-dot line* is survival for a matched US population, and *dash-dot-dot-dot line* matched survival after AVR for entire group. *AVR*, Aortic valve replacement.

the results were equivalent. Thereafter, repairs had better durability.

Other underlying pathologies were not associated with difference in propensity-adjusted risk of reoperation ($P >$ .08; Table 2, Figure 5). It is interesting that among those in whom tailoring was performed, the most common indication for reoperation was stenosis (Table 3). Clearly, overly vigorous tailoring in an attempt to reduce regurgitation can produce aortic valve stenosis.

DISCUSSION

Principal Findings

This study shows that excellent results, with few reoperations and low mortality, can be achieved with aortic valve and root-preserving procedures for a diverse group of pathologies. Indeed, the approximate 95% freedom from reoperation at 12 years for tricuspid valves is encouraging and better than for biologic valves. As expected, age, aortic dissection, and degenerative aneurysms were strongly associated with worse late survival; no other factor, including type of root-preserving procedure and cause of root pathology, was a risk factor for reduced late survival. Survival after reimplantation and remodeling operations, and in patients with Marfan syndrome and bicuspid valves after operation, despite severity of disease, was better than that of their counterparts in the general population and considerably better than that of patients with bioprostheses. Moreover, patients with bioprostheses were more likely to die

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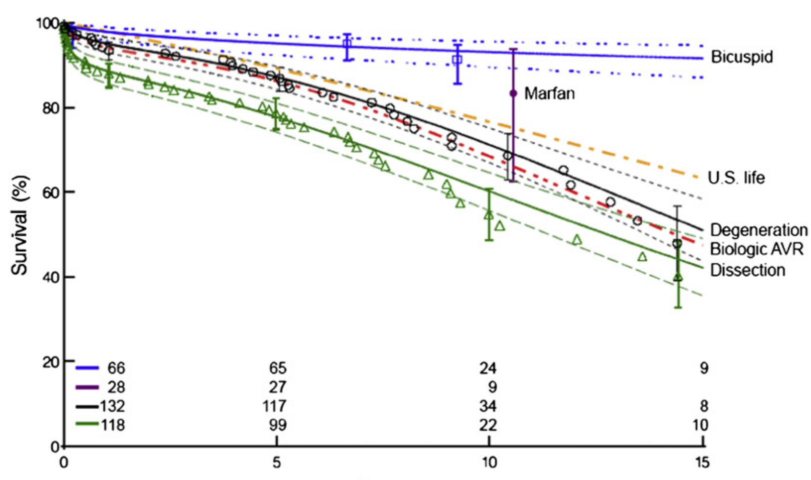

FIGURE 2. Survival according to underlying pathology. Format is as in Figure 1. Single death among patients with Marfan syndrome is represented only by an actuarial estimate at time of death (*purple filled circle*). *AVR*, Aortic valve replacement.

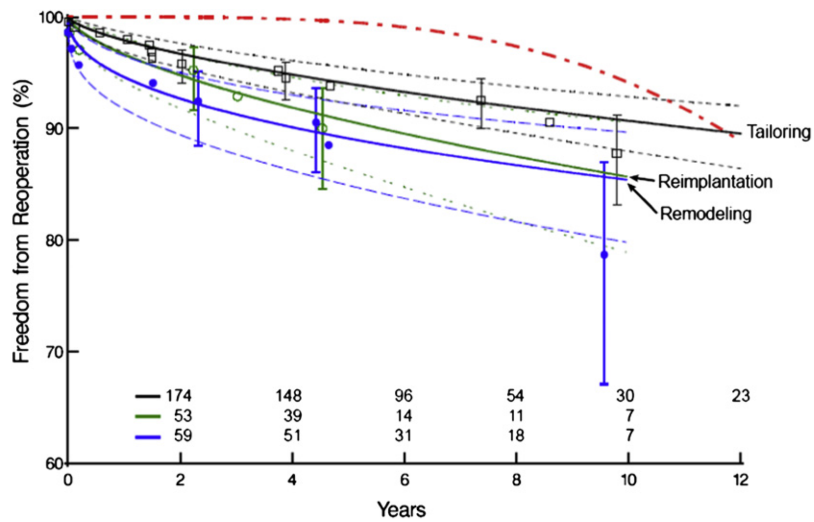

FIGURE 3. Unadjusted freedom from reoperation according to procedure. Format is as in Figure 1. For reference, *dot-dash-dot line* represents age-matched reoperation for structural valve deterioration of an aortic valve bioprosthesis.

in this matched population after 7 years, corresponding with increasing valve failure, with further divergence from repair and US population survival curves. This is gratifying. Indeed, in patients with Marfan syndrome (one of the more extensively studied subgroups), for whom the average age of death used to be 32 years, 10-year survival was 100%, and survival is now more than 70 years unless they have undergone surgery for aortic dissection; then, 5-year survival is only 50% to 70% after surgery.[33,34]

The finding that a longer aortic clamp time and an elephant trunk procedure decreased early survival is not surprising, because these variables are markers of more extensive and complex operations. Nevertheless, we have reported 98% 30-day survival for recently operated patients undergoing an elephant trunk procedure.[35] Late survival was similar after reimplantation and remodeling root-preserving procedures. Less invasive surgery was also associated with higher early mortality in these complex operations. Thus, more recently, a minimally invasive approach has been used only for root remodeling or tailoring, but not for reimplantation of the aortic valve or arch procedures.

TABLE 2. Incremental risk factors for reoperation

Variable	Coefficient ± SE	*P*	Reliability (%)*
Type of procedure			
Reimplantation vs tailoring	0.60 ± 0.60	.3	28
Remodeling vs tailoring	0.41 ± 0.50	.4	28
Propensity score for reimplantation group	0.55 ± 1.3	.7	—
Propensity score for remodeling group	2.1 ± 1.6	.2	—
Bicuspid aortic valve	1.4 ± 0.50	.002	58

SE, Standard error. *Percent of time factor appeared in 1000 bootstrap analysis.

Nonadjusted risk of reoperation was influenced by the presence of a bicuspid aortic valve; nevertheless, freedom from reoperation was 77% at 10 years for such patients, comparable to a previous report of 79% for isolated bicuspid aortic valve repairs without root or ascending aorta repairs. Despite failures, reoperations were successful in achieving 10-year survival of 93% and 15-year survival of approximately 92% in these patients. Even so, we are exploring new options to achieve even better results, similar to the 97% 9-year freedom from reoperation achieved in patients with tricuspid aortic valves.[36-39] There have been reports that remodeling may be associated with a greater risk of reoperation, particularly in patients with Marfan syndrome.[3,13,17] Failures in the Marfan group were with remodeling operations, not reimplantation, as we have previously reported.[34]

In this study, operative procedure was selected according to underlying pathology as described in the ''Patients and Methods'' section, and the results are nearly superimposable for freedom from reoperation for the modified David reimplantation, remodeling, or sinotubular junction tailoring. David and colleagues,[8,10,17] Sarsam and Yacoub,[9] and others[3,5,12,14,15,19,23,40] have also reported excellent late results with both reimplantation and remodeling. Of interest, we referenced survival to the general population and found that, following the initial early hazard phase after operation, the hazard function of our patients for mortality closely tracked that of the population. We also referenced aortic valve reoperation to expected reoperation based on structural valve deterioration of bioprostheses, which is known to be age related. We found that few (n = 1) of the reoperations for our patients were for structural valve deterioration, but for other earlier indications. Moreover, it should be noted that

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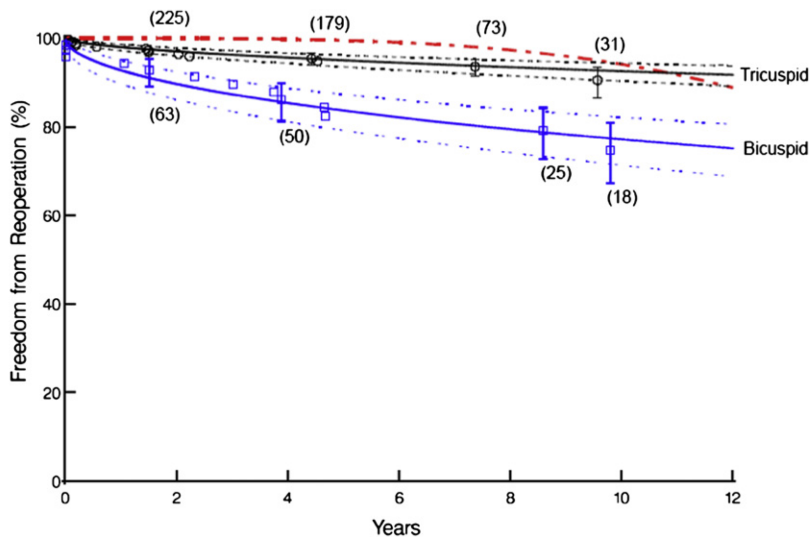

FIGURE 4. Unadjusted freedom from reoperation after bicuspid or tricuspid valve procedure ($P = .002$). Format is as in Figure 1. *Dash-dot-dash line* represents age-matched reoperation for structural valve deterioration of an aortic valve bioprosthesis.

although the curves for reoperation cross at approximately 10 years, except bicuspid valves (the latter ~14 years by extrapolation), the additional benefits of repair are better survival, better hemodynamics, and less risk of stroke and endocarditis.[1] Of note, we have previously reported the hemodynamic benefits with our modification of the David reimplantation, which provides both excellent effective orifice areas and low transvalvular pressure gradients with valve reimplantation.[37]

Limitations

This was not a randomized study designed to compare root-sparing procedures, although we have used propensity scores to balance variables to reduce selection bias. A randomized study would be difficult to perform, because procedure selection is influenced by the underlying pathologies and operative findings based on the Commissures, Leaflets, Anulus, Sinotubular junction, and Sinuses (CLASS) schema.[1,38] Furthermore, randomizing patients with repairable valves to repair or replacement on the basis of this study and others does not seem to be justified.

Although this is a 2-institution study, it traces sequential results of mainly one of the surgeons (LGS) at both venues. Thus, this should be considered a single experience. Because volume of these procedures has increased in recent years, average follow-up is short. However, time-related methods permit analysis of patients who underwent operation early in the series, for whom follow-up is long.

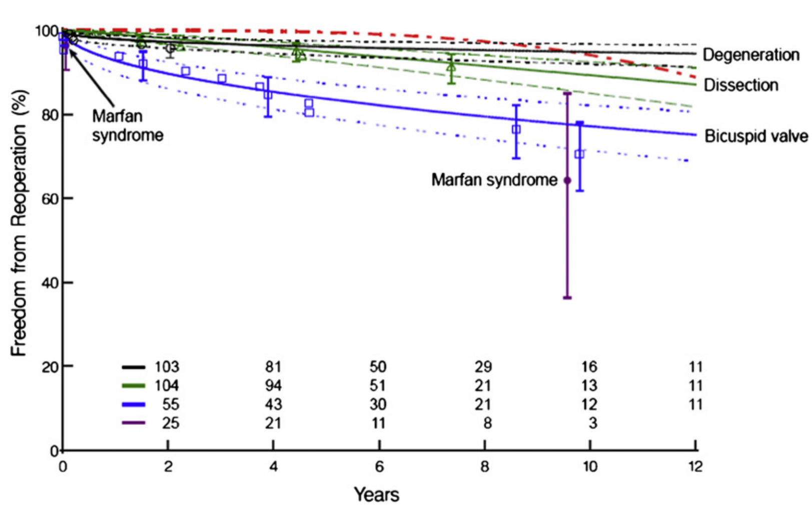

FIGURE 5. Unadjusted freedom from reoperation according to underlying pathology. Format is as in Figure 1. Two events among the Marfan syndrome patients are depicted by actuarial estimates only (*purple filled circles*). Note that in patients with Marfan syndrome, the 2 failures occurred in those undergoing remodeling, not reimplantation.

TABLE 3. Indications for reoperation by procedure

Factor	Procedure: Reimplantation (n = 7) No. (%)	Remodeling (n = 8) No. (%)	Tailoring (n = 14) No. (%)
Regurgitation	0 (0)	2 (25)	3 (21)
Stenosis	0 (0)	1 (13)	4 (29)
Endocarditis	3 (43)	0 (0)	2 (14)
New aneurysm or aortic dilatation	0 (0)	0 (0)	3 (21)
Aortic dissection	0 (0)	0 (0)	1 (7.1)
Failed repair	0 (0)	4 (50)	0 (0)
SVD	1 (14)	0 (0)	0 (0)
Uncertain	3 (29)	1 (13)	1 (7.1)

SVD, Structural valve deterioration.

CONCLUSIONS

On the basis of the excellent results of this study and other reports, we recommend that young patients with aortic valve regurgitation accompanying aortic root pathology be managed by teams experienced in aortic valve-preserving procedures. This is because management of the root requires matching the appropriate operative procedure to the underlying pathology. Long-term benefits include excellent survival, freedom from prosthesis-related complications, and low risk of reoperation.

For patients with a tricuspid valve, even if associated with severe regurgitation, and no large cusp perforations, we recommend a reimplantation type of operation. For patients with bicuspid valves having little calcium and no stenosis, we recommend a tailoring procedure with leaflet repair or a root remodeling procedure. If patients have splaying of the sinotubular junction and less than severe regurgitation or leaflet pathology, a tailoring procedure is associated with good results.

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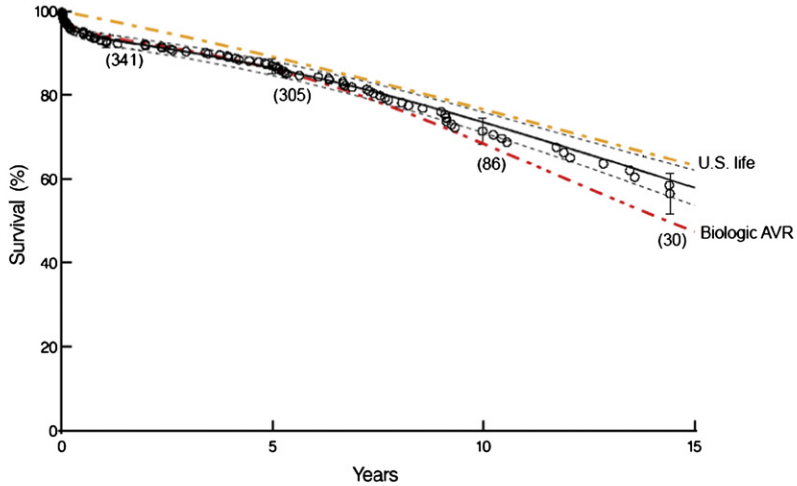

FIGURE E1. Unadjusted overall survival after operation. Note decline in survival after 7.5 years in biologic AVR patients. Each symbol represents a death, vertical bars represent asymmetric 68% confidence limits (CLs) equivalent to ±1 standard error, and numbers in parentheses represent patients remaining at risk. *Solid line* is an independently derived parametric survival estimate enclosed within dashed 68% CLs. For reference, *dash-dot-dash line* is survival for a matched US population, and *dash-dot-dot-dot line* matched survival after AVR for entire group. *AVR,* Aortic valve replacement.

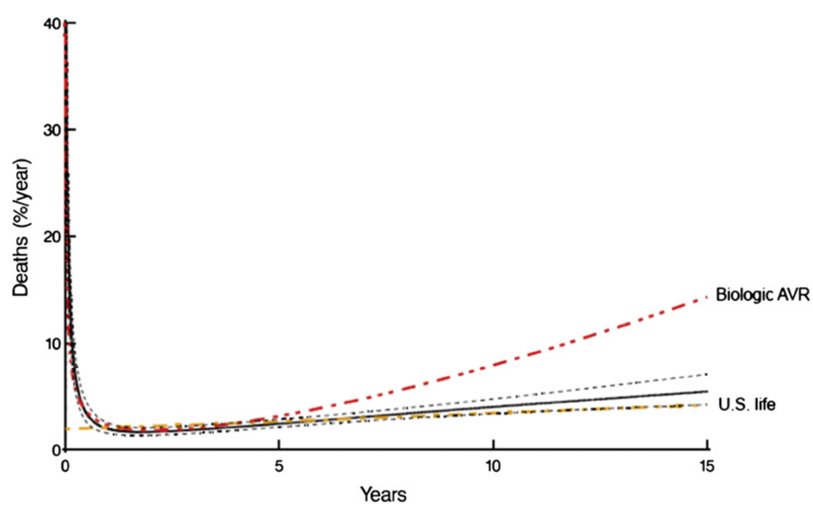

FIGURE E2. Unadjusted overall hazard function (instantaneous risk) for death. Note increase in deaths after 7.5 years in biologic AVR patients. *Solid line* is hazard estimate enclosed within 68% CLs. For reference, *dot-dash-dot line* is hazard function for matched US population, and *dash-dot-dot-dot line* is hazard function for matched population after AVR for entire group. *AVR,* Aortic valve replacement.

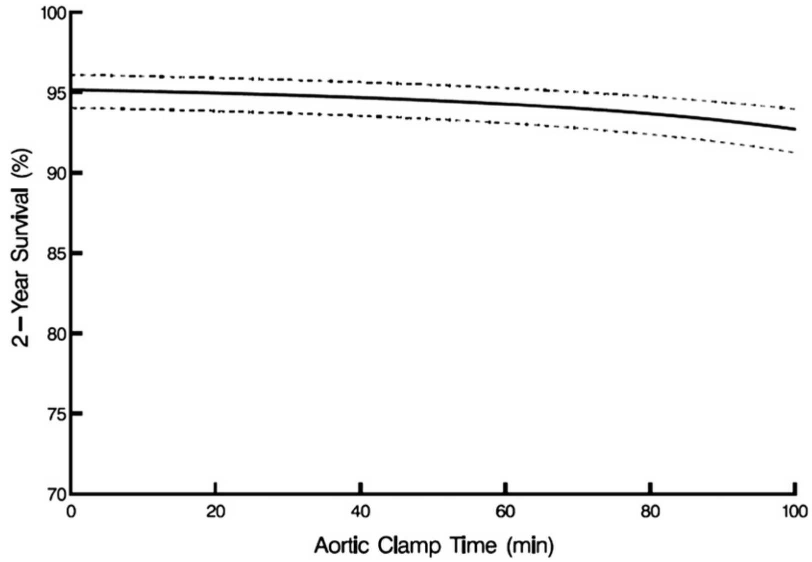

FIGURE E3. Unadjusted 2-year survival according to aortic clamp time.

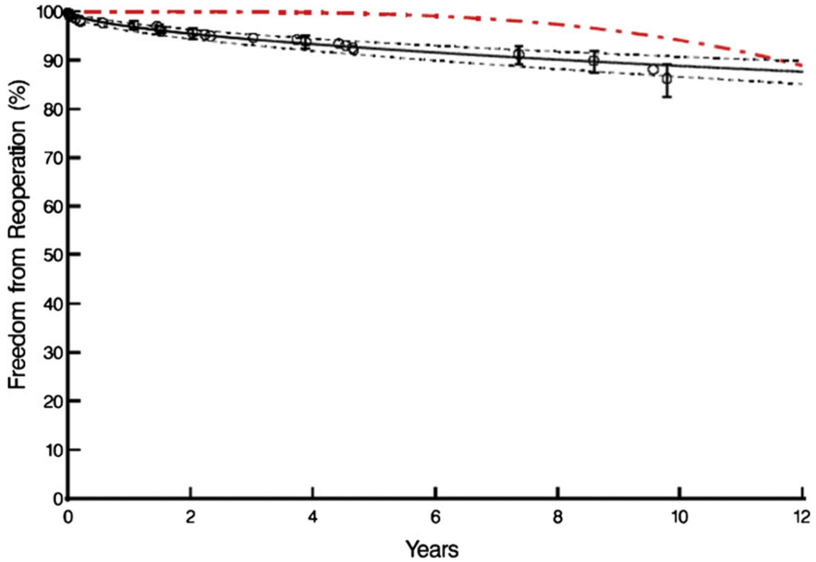

FIGURE E4. Unadjusted freedom from aortic valve reoperation. Format is as in Figure E1. *Dash-dot-dash line* represents age-matched reoperation for structural valve deterioration of an aortic valve bioprosthesis.

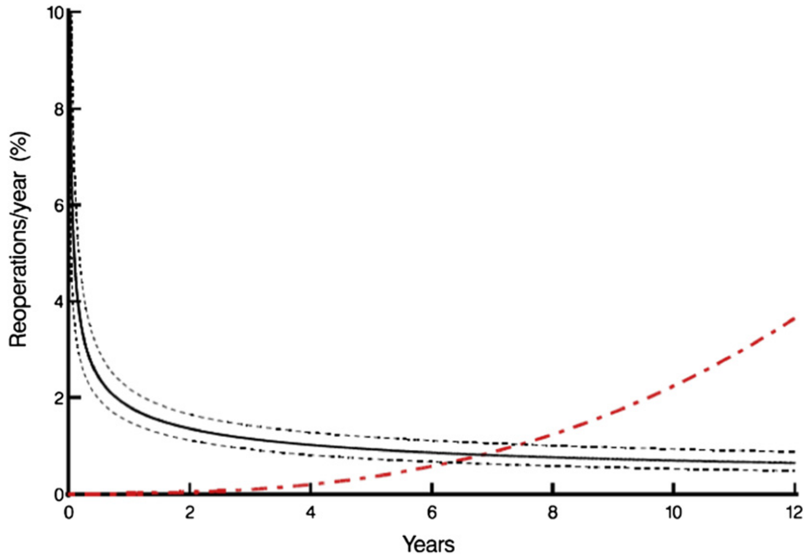

FIGURE E5. Unadjusted hazard function for reoperation. Note increasing rate of reoperation after 7 years in patients with aortic valve bioprostheses. Format is as in Figure E2, except that *dash-dot-dash line* is for age-matched rate of structural valve deterioration of aortic valve bioprostheses.

TABLE E1. Patient characteristics and operative details according to aortic valve-preserving technique

	Reimplantation (total n = 72)		Remodeling (total n = 72)		Tailoring (total n = 222)		
Variable	n*	No. (%) or mean ± SD	n*	No. (%) or mean ± SD	n*	No. (%) or mean ± SD	*P*
Demography							
Male	72	55 (76)	72	55 (76)	222	146 (66)	.09
Age (y)	72	50 ± 15	72	51 ± 16	222	60 ± 15	<.0001
Height (cm)	63	179 ± 9.5	56	180 ± 11	199	172 ± 11	<.0001
Weight (kg)	63	89 ± 20	56	89 ± 16	199	83 ± 20	.003
Body surface area (m^2)	63	2.1 ± 0.27	56	2.1 ± 0.23	199	2.0 ± 0.28	.0004
Clinical status							
NYHA class	63		56		199		.09†
I		32 (51)		20 (36)		81 (41)	
II		27 (43)		26 (46)		81 (41)	
III		4 (6.4)		8 (14)		23 (12)	
IV		0 (0)		2 (3.6)		14 (7)	
Emergency operation	71	2 (2.8)	71	14 (21)	218	73 (33)	<.0001
Aortic pathophysiology							
Aortic dissection	72	11 (15)	72	19 (26)	222	102 (46)	<.0001
Marfan syndrome	72	23 (32)	72	12 (17)	222	3 (1.3)	<.0001
Annuloaortic ectasia	72	9 (13)	72	10 (14)	222	0 (0)	<.0001‡
Bicuspid aortic valve	72	5 (6.9)	72	17 (24)	222	52 (23)	.008
Cardiac comorbidity							
Coronary artery disease§	71	9 (13)	72	16 (22)	219	69 (32)	.005
Preoperative AV regurgitation grade	72		71		222		.3†
0		9 (13)		16 (23)		23 (10)	
1+		8 (11)		12 (17)		37 (17)	
2+		16 (22)		22 (31)		63 (28)	
3+		26 (36)		14 (20)		54 (24)	
4+		13 (18)		7 (9.9)		45 (20)	
Ejection fraction (%), echo	68	57 ± 7.7	67	56 ± 9.5	185	57 ± 10	.9
Noncardiac comorbidity							
Previous stroke	72	4 (5.6)	72	4 (5.6)	222	23 (10)	.3
Peripheral arterial disease	72	8 (11)	72	10 (14)	222	46 (21)	.12
Cholesterol ($mg \cdot dL^{-1}$)	51	194 ± 30	37	193 ± 36	135	188 ± 41	.6
Triglycerides ($mg \cdot dL^{-1}$)	51	166 ± 100	34	147 ± 76	134	138 ± 99	.05
Creatinine ($mg \cdot dL^{-1}$)	71	0.95 ± 0.25	71	1.0 ± 0.30	215	1.3 ± 1.4	.05
Procedural							
Less invasive approach	72	5 (6.9)	72	9 (13)	221	15 (6.8)	.3
Operative extent	72		72		222		
Ascending aorta		36 (50)		30 (42)		59 (27)	.0004
Ascending and arch‖		27 (38)		31 (43)		163 (73)	<.0001
Distal arch		0 (0)		1 (1.4)		0 (0)	.4‡
Concomitant aortic procedure							
Descending aorta	55	1 (1.8)	66	7 (11)	186	16 (8.6)	.1‡
Descending aorta elephant trunk graft	72	4 (5.6)	72	3 (4.1)	221	23 (10)	.16
Thoracoabdominal	55	2 (3.6)	66	1 (1.5)	186	16 (8.6)	.16
Concomitant CABG	72	7 (9.7)	72	16 (22)	221	58 (26)	.02
CPB time (min)	70	140 ± 25	72	137 ± 41	214	116 ± 50	<.0001
Aortic clamp time (min)	71	114 ± 21	72	100 ± 35	213	73 ± 36	<.0001

AV, Aortic valve; *CABG*, coronary artery bypass grafting; *CPB*, cardiopulmonary bypass; *NYHA*, New York Heart Association; *SD*, standard deviation. *Data available. †Cochran–Mantel–Haenszel statistic. ‡Fisher's exact test. §Number of systems with ≥ 50% stenosis. ‖*Arch* refers to total arch or hemiarch replacement. Note that more patients undergoing tailoring had arch repairs, likely reflecting older age, more extensive disease, emergency operation, and aortic dissection. When the arch is not dilated, arch replacement is avoided except in cases of aortic dissection.

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TABLE E2. Factors considered in multivariable models

Preoperative	
Demography:	Gender, age at operation (y), height (cm), weight (kg), body surface area (m^2), body mass index ($kg \cdot m^{-2}$)
Symptoms:	New York Heart Association functional class (I–IV), Canadian Angina class (0–4), emergency operation
Ventricular function:	Infarction on echocardiogram, myocardial infarction, left ventricular ejection fraction
Pathology:	Aortic dissection, Marfan syndrome, bicuspid aortic valve, aortic valve regurgitation, aortic valve regurgitation grade
Cardiac comorbidity:	Atrial fibrillation, ventricular arrhythmia, stroke
Noncardiac comorbidity:	History of smoking, history of peripheral arterial disease, previous stroke, creatinine, coronary artery disease
Operative	
Support:	Cardiopulmonary bypass time (min), aortic clamp time (min)
Surgery type:	Ascending aorta, ascending aorta+arch, reimplantation, remodeling, number of sinuses remodeled in patients undergoing remodeling, resuspension, descending elephant trunk graft, coronary artery bypass grafting, number of coronary arteries bypassed, minimally invasive procedure, coronary arteries implanted into graft
Experience:	Date of operation

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TABLE E3. Factors associated with type of procedure performed*

Variable	Reimplantation vs tailoring (coefficient ± SE)	*P*	Remodeling vs tailoring (coefficient ± SE)	*P*
Age†	–1.3 ± 0.21	<.0001	–0.92 ± 0.19	<.0001
Emergency operation	–3.3 ± 0.75	<.0001	–0.85 ± 0.37	.02
Bicuspid aortic valve	–3.2 ± 0.58	<.0001	–1.0 ± 0.39	.008
Aortic regurgitation	0.31 ± 0.14	.03	–0.21 ± 0.12	.07
Date of operation‡	1.9 ± 0.45	<.0001	0.78 ± 0.33	.02

SE, Standard error. *Parsimonious polytomous model. †(Age/50), exponential transformation. ‡Ln(date), natural logarithmic transformation.

TABLE E4. Propensity model for type of procedure performed*

Variable	Reimplantation vs tailoring (coefficient ± SE)	*P*	Remodeling vs tailoring (coefficient ± SE)	*P*
Male	1.0 ± 0.42	.02	0.38 ± 0.36	.3
Age†	–1.2 ± 0.25	<.0001	–0.90 ± 0.22	<.0001
Emergency operation	–3.4 ± 0.78	<.0001	–0.78 ± 0.39	.04
Ejection fraction‡	0.74 ± 0.98	.5	–0.36 ± 0.72	.6
CAD	–0.83 ± 0.48	.08	–0.11 ± 0.38	.8
PAD	–0.42 ± 0.52	.9	0.07 ± 0.44	.9
Stroke	–0.04 ± 0.65	>.9	–0.49 ± 0.60	.4
History of smoking	0.20 ± 0.36	.6	0.015 ± 0.32	>.9
Creatinine	–0.66 ± 0.55	.2	–0.34 ± 0.26	.2
Bicuspid aortic valve	–3.5 ± 0.60	<.0001	–1.2 ± 0.40	.004
Aortic regurgitation	0.40 ± 0.16	.01	–0.21 ± 0.12	.08
Date of operation§	2.0 ± 0.48	<.0001	0.79 ± 0.34	.02

CAD, Coronary artery disease; *PAD*, peripheral arterial disease; *SE,* standard error. *Polytomous model. †(Age/50), exponential transformation. ‡Ln(ejection fraction), logarithmic transformation. §Ln(date), natural logarithmic transformation.

TABLE E5. Incremental risk factors for death

Variable	Coefficient ± SE	*P*	Reliability (%)*
Early hazard phase			
Type of procedure			14
Reimplantation vs tailoring	0.32 ± 0.93	.7	
Remodeling vs tailoring	–1.2 ± 1.1	.3	
Propensity score for reimplantation group	–3.6 ± 2.4	.1	—
Propensity score for remodeling group	3.6 ± 3.3	.3	—
Older age†	0.88 ± 0.38	.02	53
Less invasive procedure	2.0 ± 0.70	.004	52
Longer aortic clamp time‡	0.32 ± 0.089	.0004	54
Elephant trunk graft	1.2 ± 0.58	.04	57
Cleveland Clinic vs Lahey	1.9 ± 1.3	.1	—
Late hazard phase			
Type of procedure			12
Reimplantation vs tailoring	–0.31 ± 0.56	.6	
Remodeling vs tailoring	0.094 ± 0.45	.8	
Propensity score for reimplantation group	–2.1 ± 1.4	.1	—
Propensity score for remodeling group	–3.1 ± 2.1	.1	—
Older age†	0.62 ± 0.2	.002	99
Cleveland Clinic vs Lahey	0.83 ± 0.58	.2	—
Pathology			56
Dissection	1.8 ± 0.63	.005	
Degeneration	1.6 ± 0.69	.02	

SE, Standard error. *Percent of time factor appeared in 1000 bootstrap analyses. Factors represented in 50% or more of models are considered reliable (50% probability that $P \leq .05$). †(Age/50), exponential transformation. ‡(Aortic clamp time/80), exponential transformation.

TABLE E6. Mode of late death by pathology

Factor	Pathology			
	Aortic dissection (n = 48) No. (%)	Marfan syndrome (n = 1) No. (%)	Bicuspid aortic valve (n = 4) No. (%)	Degeneration (n = 36) No. (%)
Cardiac			1 (25)	
Heart failure	3 (6.3)			1 (2.8)
Endocarditis			1 (25)*	
Arrhythmia				1 (2.8)
Ischemia				2 (5.6)
NOS	1 (2.1)			1 (2.8)
Aneurysm rupture or dissection	3 (6.3)			1 (2.8)
Sudden	3 (6.3)			1 (2.8)
Stroke	4 (8.3)			2 (5.6)
Respiratory failure	3 (6.3)			2 (5.6)
Pulmonary embolism			1 (25)	
Renal failure	2 (4.2)			
Gastrointestinal	1 (2.1)			
Cancer	2 (4.2)			4 (11)
Sepsis	1 (2.1)			
Trauma	2 (4.2)			
Noncardiac (NOS)				1 (2.8)
Systemic inflammatory response syndrome	1 (2.1)			1 (2.8)
MSOF	2 (4.2)			1 (2.8)
Uncertain	20 (42)	1 (100)	1 (25)	18 (50)

MSOF, Multiple system organ failure; *NOS*, not otherwise specified. *Died at reoperation.

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