Reoperation after aortic root replacement and its impact on long-term survival

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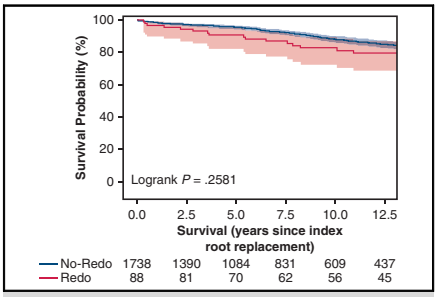
ABSTRACT

Objective: Reoperation after aortic root replacement (ARR) is associated with increased operative risk and complexity. This study evaluated clinical outcomes and reoperation rates in patients undergoing ARR.

Methods: From 2004 to 2021, 2700 adult patients underwent an ARR in a 2-institution database. Among 2542 surviving patients, 705 patients who had a history of previous cardiac surgery as well as 11 patients who underwent transcatheter aortic valve replacement after index ARR were excluded. Among the finalized cohort of 1826 patients, 88 (4.8%) underwent a reoperation (REDO) on the aortic valve or proximal aorta (root/ascending) a mean of 3.1 years after index ARR whereas 1738 (95%) did not undergo reoperation (no-REDO). A subgroup analysis was performed among those undergoing reoperation by indication including valve dysfunction (48%), endocarditis/graft infection (33%), and aortic aneurysm/dissection/rupture (12%). Reoperative indication was unknown in 6 patients (7%).

Results: The REDO group was younger at time of index ARR (52 vs 58 years, $P < .0001$) and had more bicuspid aortic valves (56% vs 37%, $P = .0003$). Most patients underwent modified Bentall ARR (61%), whereas 38% underwent a valve-sparing root replacement. Index root operations were similar between groups. At time of reoperation, 53% underwent aortic valve replacement and 35% underwent redo root replacement. Long-term survival was similar between REDO and no-REDO groups (80% vs 85%, $P = .26$) and reoperation was not a risk factor for late mortality (hazard ratio, 1.31; $P = .26$); however, REDO ARR was a risk factor for late mortality (hazard ratio, 2.41; $P = .02$).

Conclusions: The incidence of aortic valve and/or proximal aorta reoperation after index ARR is relatively low at 4.8%; however, root reoperation is a risk factor for late mortality. (JTCVS Open 2024;21:45-57)



Proximal aortic reoperation after root replacement does not impact long-term survival.

CENTRAL MESSAGE

The incidence of reoperation after aortic root replacement is 4.8% and occurs in younger patients with bicuspid aortic valves. Reoperation does not impact long-term survival.

PERSPECTIVE

Among patients undergoing aortic root replacement, 4.8% required reoperation, predominantly for valve dysfunction. Other indications included endocarditis and aortic pathology. The index root procedure did not impact reoperation and reoperation overall did not impact long-term survival; however, a redo-root is associated with worse survival.

Aortic root replacement (ARR) has become an established treatment for aortic root pathology and is associated with low morbidity and mortality.[1] The modified Bentall procedure comprises the majority of root-replacement procedures (81% in a recent Society of Thoracic Surgeons [STS] database study of elective

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Abbreviations and Acronyms

ARR = aortic root replacement
BAV = bicuspid aortic valve
CI = confidence interval
HR = hazard ratio
IRB = institutional review board
STS = Society of Thoracic Surgeons
VSRR = valve-sparing root replacement

ARRs[1]), although valve-sparing root replacement and the Ross procedure are alternative strategies being increasingly used. Many factors contribute to the decision regarding the specific type of ARR to perform, including patient age, etiology of aortic pathology, aortic valve anatomy and function, connective tissue disease, and surgeon experience. In addition to short-term outcomes, long-term outcomes including survival and need for reoperation have been studied.

Reoperation rates throughout the literature for aortic valve disease and proximal aortic pathology after root replacement are highly variable, ranging from 2% to 20%,[2-7] depending on index root replacement procedure and subsequent indication for reoperation. With the increase in root replacement operations being performed, an increase in redo cardiac operations after root replacement is expected. Most previous studies evaluated patients undergoing reoperation after root replacement in the setting of an index root replacement. Although this study also focuses on patients requiring reoperation, it also examines and compares the short- and long-term outcomes of patients both with and without the need for reoperation after index ARR.

METHODS

This study was approved by the institutional review board (IRB) at Emory University IRB #00001479 (August 30, 2021) and Columbia University Irving Medical Center IRB #AAAU0575 (April 4, 2022), a waiver of consent was obtained, and the study was in compliance with Health Insurance Portability and Accountability Act regulations. This 2-center retrospective study involved all patients undergoing ARR between February 2004 and February 2021 at Emory and Columbia Universities, categorized as "index root replacement."

Study Population

From February 2004 to February 2021, 2700 patients underwent ARR. Patients with in-hospital mortality at index ARR (n = 158), a history of previous cardiac surgery (n = 705), and requiring transcatheter aortic valve replacement during follow-up (n = 11) were excluded. Among the remaining 1826 patients, 4.8% (n = 88) required a reoperation on the aortic valve or proximal aorta (root/ascending) a mean of 3.1 years after ARR whereas 95% (n = 1738) did not undergo reoperation (Figure 1).

Baseline characteristics, operative details, and in-hospital complications were obtained from institutional STS Adult Cardiac Surgery Databases and medical record review. STS Adult Cardiac Surgery Database definitions were followed whenever available. Follow-up data, including reoperation and survival, were obtained via chart review and by directly contacting patients and referring cardiologists. The survival status was supplemented by the Centers for Disease Control and Prevention National Death Index (accessed March 29, 2022, data complete through December 31, 2021). Mean follow-up time was 6.5 ± 4.5 years. Follow-up index[8] was 0.83.

Operative Techniques

All patients in this cohort underwent ARR and operative indications followed published guidelines at time of surgery. The type of ARR was at the operating surgeon's discretion and was determined on the basis of various factors including patient age, comorbidities, hemodynamics, status of the operation, native valve characteristics (free margin thickening or calcification), native valve tissue integrity, and surgeon preference. Valve-sparing root replacement (VSRR) was performed using the David V reimplantation technique. Most VSRRs were performed with tailored straight tube grafts or Gelweave Valsalva graft. The choice of valve was at the operating surgeon's discretion.

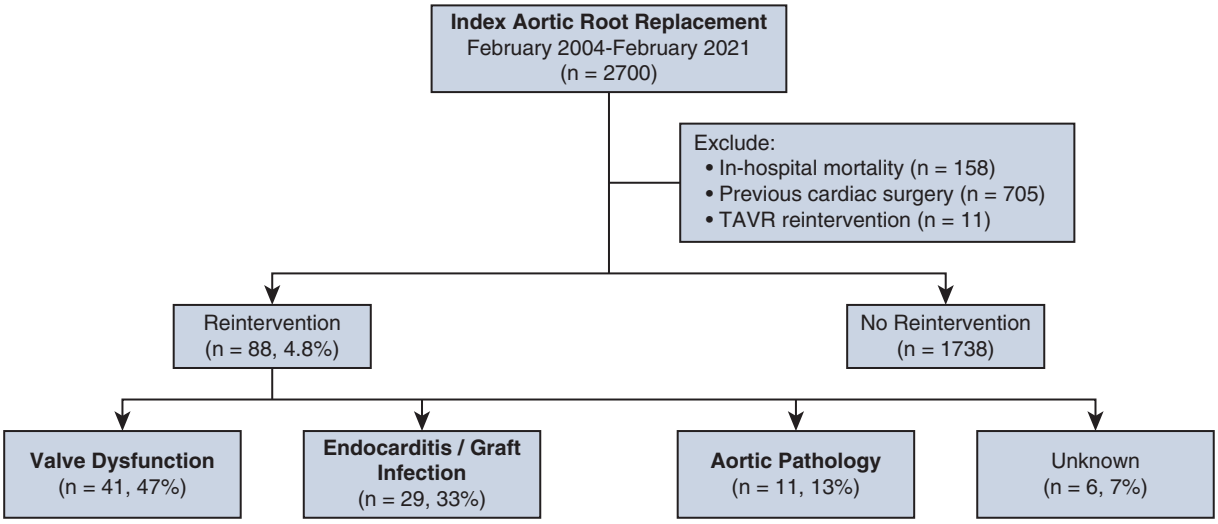

FIGURE 1. Consolidated Standards of Reporting Trials diagram of the study population. *TAVR*, Transcatheter aortic valve replacement.

Statistical Analysis

Initial analysis provided descriptive information on the demographic, clinical, and surgical characteristics. Continuous variables were summarized by mean (standard deviation) or median (lower quartile, upper quartile) and categorical variables were reported as count (percentage) in tables. Categorical comparisons between REDO and no-REDO groups were performed using χ^2 tests or Fisher exact tests as appropriate. Continuous data were compared using the Student *t* test or Wilcoxon rank sum tests as appropriate. Missingness was handled with analysis, where statistical methods were unaffected by missing values. A subgroup analysis was performed among the REDO group on the basis of indication for reoperation; patients whose reoperative indication was unable to be determined were excluded from the subgroup analysis (n = 9). Categorical comparisons between reoperation indication subgroups were performed using analysis of variance test. Univariable regression was initially performed to assess risk factors for reoperation of the aortic valve or proximal aorta and late mortality. Cox proportional hazard modeling was used to assess risk for of reoperation of the aortic valve or proximal aorta by adjusting for age, sex, hypertension, bicuspid aortic valve (BAV), and status (elective, urgent, emergent, salvage) for index ARR. Cox proportional hazard modeling was used to assess risk for late mortality of age, diabetes, hypertension, chronic lung disease, renal failure on dialysis, peripheral vascular disease, BAV, urgent/emergent/emergent salvage index root replacement, VSRR, and root reoperation. Variables were selected for the multivariable models based on univariate analysis. Crude survival curves since operation and reoperation were estimated using the nonparametric Kaplan-Meier method.

RESULTS

Overall Demographics

The median age at the time of index ARR was 58 years, with the REDO group being younger than the no-REDO group (52 vs 58 years, $P < .0001$). The REDO group had fewer comorbidities including dyslipidemia (41% vs 55%, $P = .01$) and hypertension (53% vs 74%, $P < .0001$). The REDO group had more BAVs (56% vs 37%, $P = .0003$). The most common indication for index root replacement was aortic valve dysfunction (Table 1).

Within the REDO group, the median age at the time of reoperation was similar across the various indications: valve dysfunction (48 years) at index root replacement, endocarditis/graft infection (53 years), and aortic aneurysm/dissection/rupture (52 years) ($P = .32$) (Table 2). Preoperative comorbidities at time of index root replacement were similar among the different indications for reoperation.

Index Operative Data

The REDO group had more index root replacements performed in the elective setting, whereas the no-REDO

TABLE 1. Preoperative demographics of the entire cohort

Variable	Total (n = 1826)	REDO (n = 88)	No REDO (n = 1738)	*P* value
Age, y	58 (46, 67)	52 (41, 61)	58 (46, 67)	**<.0001**
Sex, male	1532 (84)	79 (90)	1453 (84)	.12
BMI	27.8 (24.8, 31.5)	27.4 (24.8, 30.2)	27.8 (24.8, 31.6)	.36
Diabetes	202 (11)	5 (5.7)	197 (11)	.10
Dyslipidemia	962 (54)	36 (41)	926 (55)	**.01**
Hypertension	1336 (73)	47 (53)	1289 (74)	**<.0001**
Chronic lung disease	216 (12)	7 (8.0)	209 (12)	.25
CKD	299 (16)	9 (10)	290 (17)	.12
Renal failure on dialysis	24 (1.3)	1 (1.1)	23 (1.3)	1.0
PVD	103 (5.7)	3 (3.4)	100 (5.8)	.48
CVD	124 (6.8)	5 (5.7)	119 (6.9)	.67
CVA	51 (2.9)	2 (2.3)	49 (2.9)	1.0
LVEF	55 (53, 60)	55 (54, 60)	55 (53, 60)	.56
Connective tissue disease	81 (4.4)	4 (4.6)	77 (4.4)	.79
Bicuspid aortic valve	687 (38)	49 (56)	638 (37)	**.0003**
Previous cardiac surgery	0 (0)	0 (0)	0 (0)	–
Indication				.13
Valve dysfunction	1061 (58)	59 (67)	1002 (58)	.08
Dissection	159 (8.7)	6 (6.8)	153 (8.8)	.52
Aneurysm	590 (32)	21 (24)	569 (33)	.08
Endocarditis	15 (0.8)	2 (2.3)	13 (0.6)	.16
Other	1 (0.1)	0 (0)	1 (0.1)	1.0

Data are presented as median (25%, 75%) for continuous data and n (%) for categorical data. Bold indicates statistical significance ($P < .05$). *BMI*, Body mass index; *CKD*, chronic kidney disease; *PVD*, peripheral vascular disease; *CVD*, cerebrovascular disease; *CVA*, cerebrovascular accident; *LVEF*, left ventricular ejection fraction.

TABLE 2. Preoperative demographics of the reoperation group

Variable	Reoperation (n = 88)	Valve dysfunction (n = 41)	Endocarditis/graft infection (n = 29)	Aortic aneurysm/ dissection/rupture (n = 11)	Unknown (n = 6)	*P* value
Age, y	52 (41, 61)	48 (39, 61)	53 (46, 58)	52 (45, 62)	44 (33, 51)	.32
Sex, male	79 (90)	38 (90)	27 (93)	8 (73)	6 (100)	.21
BMI	27.4 (24.8, 30.2)	26.9 (24.6, 29.9)	29.1 (25.9, 31.4)	24.2 (23.0, 28.3)	26.7 (23.4, 31.0)	**.02**
Diabetes	5 (5.7)	3 (7.1)	2 (6.9)	0 (0)	0 (0)	1.0
Dyslipidemia	36 (41)	14 (33)	15 (52)	6 (55)	1 (17)	.22
Hypertension	47 (53)	20 (48)	19 (66)	6 (55)	2 (33)	.36
Chronic lung disease	7 (8.0)	2 (4.8)	3 (10)	2 (18)	0 (0)	.34
CKD	9 (10)	5 (12)	3 (10)	1 (10)	0 (0)	1.0
Renal failure on dialysis	1 (1.1)	0 (0)	1 (3.5)	0 (0)	0 (0)	.52
PVD	3 (3.4)	1 (2.4)	1 (3.5)	1 (9.1)	0 (0)	.62
CVD	5 (5.7)	1 (2.9)	2 (6.9)	2 (18)	0 (0)	.22
CVA	2 (2.3)	0 (0)	0 (0)	2 (18)	0 (0)	**.02**
LVEF	55 (54, 60)	55 (53, 56)	55 (54, 60)	55 (50, 55)	58 (55, 62)	.40
Connective tissue disease	4 (4.6)	2 (4.8)	2 (6.9)	0 (0)	0 (0)	1.0
Bicuspid aortic valve	49 (56)	27 (64)	14 (48)	4 (36)	4 (67)	.30
Indication						**.0004**
Valve dysfunction	59 (67)	35 (83)	18 (62)	1 (9.1)	5 (83)	**<.0001**
Dissection	6 (6.8)	1 (2.4)	2 (6.9)	3 (27)	0 (0)	.054
Aneurysm	21 (24)	6 (14)	8 (28)	6 (55)	1 (17)	**.04**
Endocarditis	2 (2.3)	0 (0)	1 (3.5)	1 (9.1)	0 (0)	.23

Data are presented as median (25%, 75%) for continuous data and n (%) for categorical data. Bold indicates statistical significance ($P < .05$). *BMI*, Body mass index; *CKD*, chronic kidney disease; *PVD*, peripheral vascular disease; *CVD*, cerebrovascular disease; *CVA*, cerebrovascular accident; *LVEF*, left ventricular ejection fraction.

group had more index root replacements performed in an urgent/emergent/emergent salvage setting ($P = .02$). Root operations were similar at time of index operation between REDO and no-REDO groups, including VSRR (41% vs 38%, $P = .53$), mechanical Bentall (7% vs 8%, $P = .77$), bio-Bentall (50% vs 54%, $P = .53$), and Ross (2.3% vs 1.4%, $P = .38$). The median valve size was similar between REDO and no-REDO groups (29 mm, $P = .97$). The REDO group underwent more ascending replacement (45% vs 32%, $P = .01$) at index root replacement (Table 3).

Patients undergoing reoperation for valve dysfunction or endocarditis/graft infection were more likely to have an elective index root replacement, whereas those undergoing reoperation for aortic aneurysm/dissection/rupture were more likely to have an urgent or emergent index root replacement. Indications for reoperation were similar among patients who had index VSRR, index modified bio-Bentall, or index modified mechanical Bentall (Table 4).

Postoperative Outcomes

After index ARR, the REDO group had more permanent pacemaker/implantable cardioverter-defibrillator implantations (10% vs 3.2%, $P = .003$). Other postoperative outcomes, including stroke, renal failure requiring dialysis, prolonged ventilation, atrial fibrillation, and postoperative lengths of stay, were similar between groups (Table E1). Among the REDO group, patients requiring reoperation for aortic pathology had longer lengths of stay at time of index root replacement (10 days) compared with reoperation for valve dysfunction (6 days) and endocarditis/graft infection (7 days) ($P = .03$) (Table E2).

Aortic Valve/Proximal Aorta Reinterventions

Incidence of reoperation was 4.8% (88/1826). In the REDO group, the primary indication was valve dysfunction (48%), with an additional 33% undergoing reoperation for endocarditis or graft infection, and 12% undergoing reoperation for aortic aneurysm, dissection, or rupture. Reoperation for valve dysfunction included reoperation for aortic insufficiency (67%) and aortic stenosis/permanent pacemaker (33%). The median time to reoperation was 3.1 (1.0, 7.9) years. Time to reoperation was shorter in patients with endocarditis/graft infection (1.1 [0.3, 1.7] years) and aortic pathology (3.0 [1.4, 7.0] years) compared with patients with valve dysfunction 6.2 [1.8, 8.9] years ($P < .0001$) (Table E2).

TABLE 3. Index operative details of the entire cohort

Variable	Total (n = 1826)	REDO (n = 88)	No-REDO (n = 1738)	*P* value
Status				**.02**
Elective	1184 (65)	70 (80)	1114 (64)	**.003**
Urgent	484 (27)	13 (15)	471 (27)	**.01**
Emergent	156 (8.5)	5 (5.7)	151 (8.7)	.33
Emergent salvage	2 (0.1)	0 (0)	2 (0.1)	1.0
AV repair	366 (20)	22 (25)	344 (20)	.23
VSRR	689 (38)	36 (41)	653 (38)	.53
Bentall				
Mechanical	139 (7.6)	6 (6.8)	133 (7.7)	.77
Bioprosthetic	973 (54)	44 (50)	929 (54)	.53
Ross	27 (1.5)	2 (2.3)	25 (1.4)	.38
Valve size, mm	29 [25, 29]	29 [25, 29]	29 [25, 29]	.97
Concomitant procedure				
Ascending replacement	599 (33)	40 (45)	559 (32)	**.01**
Hemiarch replacement	798 (44)	34 (39)	764 (44)	.33
Partial/total arch	143 (7.8)	10 (11)	133 (7.7)	.21
Mitral valve procedure	83 (4.6)	6 (6.8)	77 (4.4)	.29
CABG	291 (16)	14 (16)	277 (16)	.99
CPB time, min	179 (138, 218)	169 (131, 223)	179 (139, 218)	.39
Crossclamp time, min	151 (110, 187)	136 (98, 186)	151 (111, 187)	.11
IABP	65 (3.6)	4 (4.6)	61 (3.5)	.55

Data are presented as median (25%, 75%) for continuous data and n (%) for categorical data. Bold indicates statistical significance ($P < .05$). *AV*, Aortic valve; *VSRR*, valve-sparing root replacement; *CABG*, coronary artery bypass grafting; *CPB*, cardiopulmonary bypass; *IABP*, intra-aortic balloon pump.

Fifty-three percent of patients underwent an aortic valve replacement. The median valve size implanted at reoperation was 25 [23, 27] mm. Thirty-five percent of patients underwent redo-root replacement, 31% of patients underwent ascending replacement, and 24% of patients underwent arch replacement. Among the 689 patients who underwent initial VSRR, 36 (5.2%) required reoperation, of whom 18 (2.6%) required reoperation for valve dysfunction (aortic insufficiency [n = 10] and aortic stenosis/patient-prosthesis mismatch [n = 8]) a mean of 5.1 years after initial VSRR. Re-interventions after VSRR included redo root replacement in 31% (11/36). Overall, 30-day mortality after reoperation was 5.7% (5/88) (Table 5) and greatest in patients having reoperation for endocarditis/graft infection (14%), followed by aortic pathology (9.1%), and lowest among reoperation for valve dysfunction (0%) ($P = .07$) (Table E2). Younger age (hazard ratio [HR], 1.02; confidence interval [CI], 1.01-1.04, $P = .0004$), BAV (HR, 1.76; 95% CI, 1.15-2.70; $P = .009$), and elective index root replacement (HR, 1.69; 95% CI, 1.01-2.86; $P = .048$) were independent risk factors for reoperation of the aortic valve or proximal aorta (Table 6). Choice of root procedure (VSRR; HR, 0.94, $P = .79$, bio-Bentall; HR, 0.96, $P = .85$) was not a risk factor for reoperation (Table E3).

Survival

Overall 10-year survival was similar between the REDO and no-REDO groups (80%; 95% CI, 69%-87% vs 85%; 95% CI, 82%-87%, $P = .26$; Figure 2, *A*). Reoperation was not a significant risk factor for long-term mortality (HR, 1.31; 95% CI, 0.82-2.11, $P = .26$; Table E4). Older age (HR, 1.04; 95% CI, 1.03-1.05, $P \leq .0001$), hypertension (HR, 1.46; 95% CI, 1.00-2.11, $P = .049$), renal failure on dialysis (HR, 3.87; 1.68-8.95, $P = .002$), urgent/emergent/emergent salvage index ARR (HR, 1.78; 95% CI, 1.33-2.39, $P = .0001$), and root reoperation (HR, 2.41; 95% CI, 1.17-4.97, $P = .02$) were independent risk factors for late mortality (Table 6). After index root replacement, 10-year survival was worse among patients requiring reoperation for endocarditis/graft infection (48%; 95% CI, 27%-66%) and aortic pathology (89%; 95% CI, 43%-98%) compared with those requiring reoperation for valve dysfunction (95%; 95% CI, 80%-99%; $P = .0002$; Figure 2, *B*). Those undergoing reoperation for endocarditis/graft infection had worse survival after reoperation (8-year: 42%; 95% CI, 20%-63%) compared with undergoing reoperation for valve dysfunction (92%; 95% CI, 77%-97%) or aortic pathology (91%; 95% CI, 51%-99%, $P = .01$; Figure 2, *C*).

TABLE 4. Index operative details of the reoperation group

Variable	Reoperation (n = 88)	Valve dysfunction (n = 42)	Endocarditis/ graft infection (n = 29)	Aortic aneurysm/ dissection/rupture (n = 11)	Unknown (n = 6)	*P* value
Status						**<.0001**
Elective	70 (80)	39 (93)	23 (79)	2 (18)	6 (100)	**<.0001**
Urgent	13 (15)	2 (4.8)	5 (17)	6 (55)	0 (0)	**.001**
Emergent	5 (5.7)	1 (2.4)	1 (3.5)	3 (27)	0 (0)	**.048**
AV repair	22 (25)	13 (31)	6 (21)	1 (9.1)	2 (33)	.43
VSRR	36 (41)	18 (43)	11 (38)	4 (36)	3 (50)	.92
Bentall						
Mechanical	6 (6.8)	1 (2.4)	4 (14)	1 (9.1)	0 (0)	.26
Bioprosthetic	44 (50)	22 (52)	14 (48)	5 (45)	3 (50)	.97
Ross	2 (2.3)	1 (2.4)	0 (0)	1 (9.1)	0 (0)	.46
Valve size	29 (25, 29)	29 (29, 29)	27 (25, 29)	25 (25, 29)	25 (25, 29)	.23
Concomitant procedure						
Ascending replacement	40 (45)	27 (64)	9 (31)	3 (27)	1 (17)	**.007**
Hemiarch replacement	34 (39)	11 (26)	16 (55)	3 (27)	4 (67)	**.03**
Partial/total arch	10 (11)	3 (7.1)	2 (6.9)	4 (36)	1 (17)	**.06**
Mitral valve procedure	6 (6.8)	0 (0)	3 (10)	2 (18)	1 (17)	**.02**
CABG	14 (16)	4 (9.5)	4 (14)	4 (36)	2 (33)	.08
CPB time, min	169 (131, 223)	144 (118, 169)	198 (170, 233)	229 (199, 317)	156 (121, 200)	**.002**
Crossclamp, min	136 (98, 186)	116 (93, 148)	157 (136, 187)	188 (119, 218)	117 (105, 175)	**.01**
IABP	4 (4.5)	0 (0)	3 (10)	1 (9.1)	0 (0)	.10

Data are presented as median (25%, 75%) for continuous data and n (%) for categorical data. Bold indicates statistical significance ($P < .05$). *AV*, Aortic valve; *VSRR*, valve-sparing root replacement; *CABG*, coronary artery bypass grafting; *CPB*, cardiopulmonary bypass; *IABP*, intra-aortic balloon pump.

DISCUSSION

Reoperative cardiac surgery is known to be more complex and associated with worse outcomes[9-12] compared with primary cases,[13] including having a greater in-hospital mortality. Challenges of reoperative cardiac surgery include sternal re-entry, adhesions, and distorted anatomy. In addition to affecting short-term outcomes, reoperative cardiac surgery has been shown to hinder long-term survival. Bianco and colleagues[14] found that reoperative cardiac surgery had worse survival (66% vs 73% at 5 years, $P = .0002$) and that reoperation was an independent predictor of long-term mortality (HR, 1.30; $P = .002$);

TABLE 5. Reinterventions

Variable	Reoperation (n = 88)
Indication	
Valve dysfunction	42 (48)
Endocarditis/graft infection	29 (33)
Aortic aneurysm/dissection/rupture	11 (12)
Unknown	6 (7)
Procedure	
AVR	47 (53)
Root	36 (41)
Replacement	31 (35)
Repair*	5 (5.7)
Valves	
Bioprosthetic	57 (88)
Mechanical	8 (12)
Valve size, mm	25 (23, 27)
Ascending	26 (31)
Arch	20 (24)
30-d mortality	5 (5.7)

AVR, Aortic valve replacement. *Root repair includes repair of button pseudoaneurysms and proximal anastomosis dehiscence.

TABLE 6. Risk factors for reoperation and late mortality by multivariable analysis

Variable	Hazard ratio (95% CI)	*P* value
Reoperation		
Age	0.98 (0.96-0.99)	**.0004**
Sex, male	0.54 (0.27-1.08)	.08
Bicuspid aortic valve	1.76 (1.15-2.70)	**.009**
Urgent/emergent/salvage operation	0.59 (0.35-0.99)	**.048**
Late mortality		
Age	1.04 (1.02-1.05)	**<.0001**
Hypertension	1.46 (1.00-2.11)	**.049**
Renal failure on dialysis	3.87 (1.68-8.95)	**.002**
Urgent/emergent/salvage	1.78 (1.33-2.39)	**.0001**
Root reoperation	2.41 (1.17-4.97)	**.02**

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

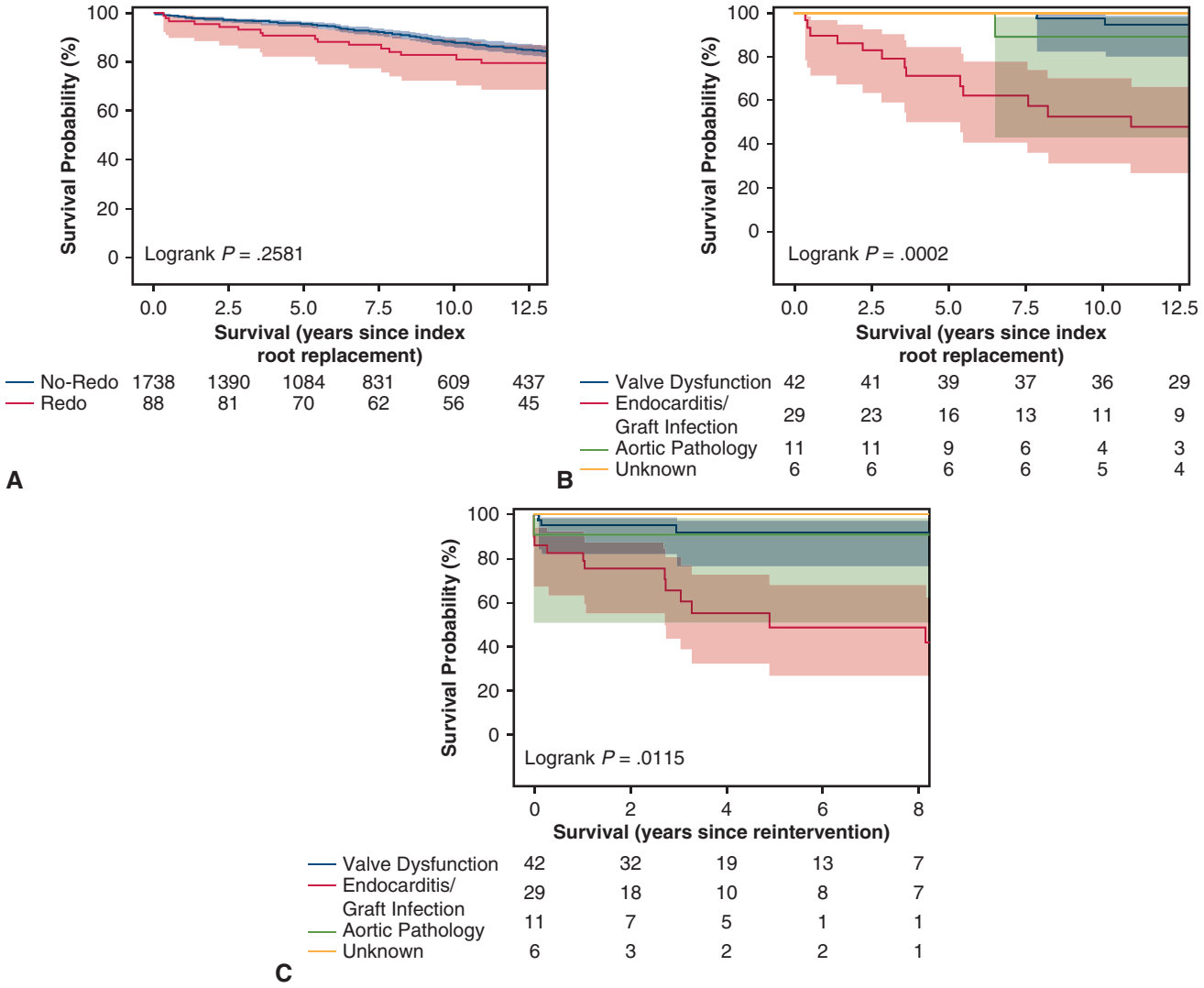

FIGURE 2. Long-term survival. A, Kaplan-Meier survival analysis of patients requiring reoperation (n = 88) compared with those without reoperation (n = 1738) after index aortic root replacement. Ten-year survival was similar between reoperation (80%; 95% CI, 69%-87%) and no reoperation (85%; 95% CI, 82%-87%]) groups ($P = .26$). B, Kaplan-Meier survival analysis of patients requiring reoperation (n = 88) by reoperation indication after index aortic root replacement. Ten-year survival was worse among patients requiring reoperation for endocarditis/graft infection (48%; 95% CI, 27%-66%) and for aortic aneurysm/dissection/rupture (89%; 95% CI, 43%-98%) compared with reoperation for valve dysfunction (95%; 95% CI, 80%-99%]) groups ($P = .0002$). C, Kaplan-Meier survival analysis of patients requiring reoperation (n = 99) by reoperation indication following reoperation. Eight-year survival was worse among patients requiring reoperation for endocarditis/graft infection (42%; 95% CI, 20%-63%) compared with reoperation for valve dysfunction (92%; 95% CI, 77%-97%) and aortic aneurysm/dissection/rupture (91%; 95% CI, 51%-99%) groups ($P = .01$). *CI*, Confidence interval.

however, aortic valve/root procedures comprised only approximately 35% of that cohort.

The aim of this study was to evaluate the reoperation rates on the aortic valve or proximal aorta after ARR, indications for reoperation, and the impact of reoperation on long-term survival. The incidence of reoperation in this study was 4.8%, which is similar to that reported in the literature.[3,6] The time to reoperation varied and was determined on the basis of the clinical indication, being shortest for endocarditis/graft infection (1.1 years) and longer for valve dysfunction (6.2 years). Reoperation did not impact long-term survival (10-year survival: 80% in the REDO group vs 85% in the no-REDO group, $P = .26$) with an HR of 1.31, $P = .26$; however, those requiring reoperation for endocarditis/graft infection had worse survival among patients undergoing reoperation.

Reoperative root replacement has been associated with increased mortality, up to 18%[13,15,16] and is being increasingly performed because of the increasing number of ARRs,

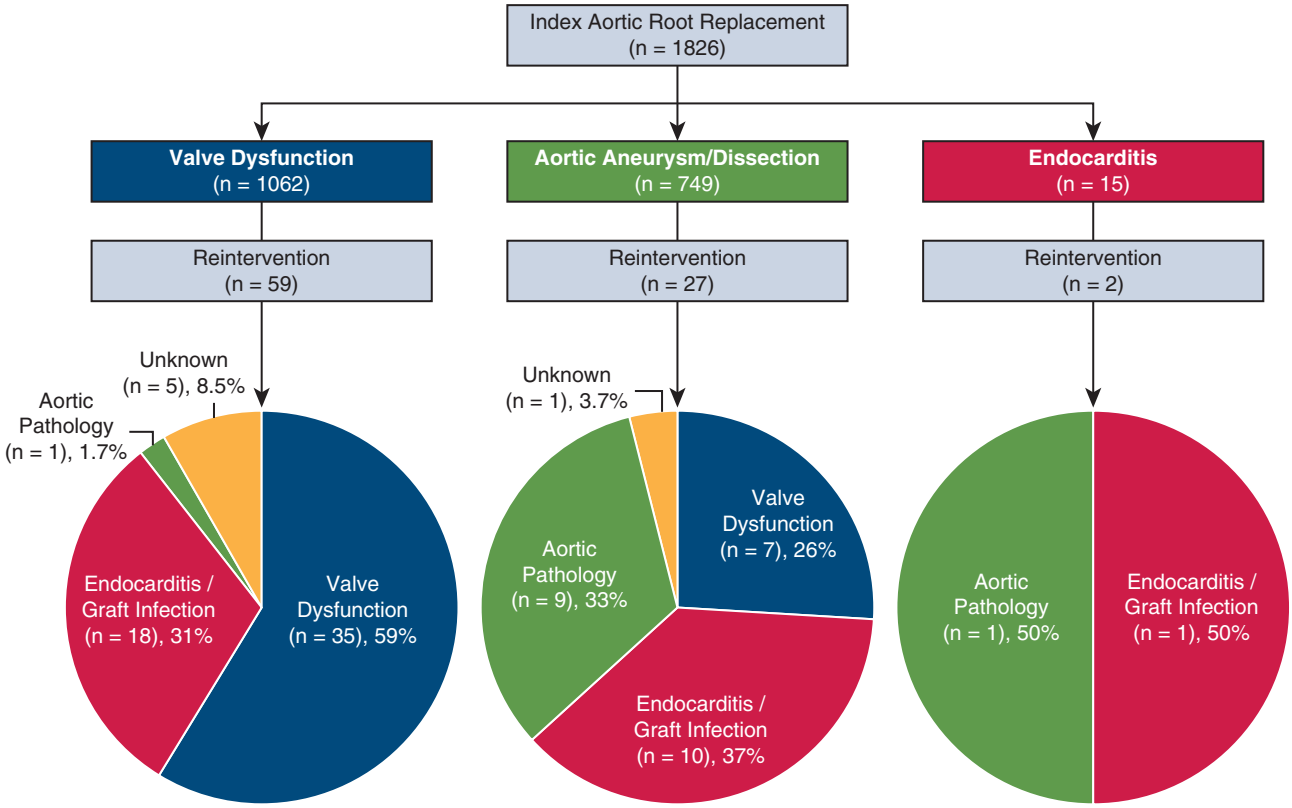

FIGURE 3. Indications for reoperation by index aortic root.

reoperative aortic root reconstructions, and an aging population.[16] Redo-root replacement is particularly complex and associated with worse outcomes because of the risk of sternal re-entry but also coronary reimplantation. Using the STS database, Ogami and colleagues[17] reported an incidence of redo-ARR of 26.5% with an operative mortality of 10.8%, which is similar to our study, in which 35% of patients required a redo-root replacement with a 30-day mortality of 10%, greater than that of the index root replacement (5.1%). Root reoperation was an independent predictor of long-term mortality (HR, 2.41, $P = .02$).

Previous studies have focused on reoperation after ARR in the setting of the index root procedure (ie, type of index ARR, setting of index ARR) or on redo-root replacements. This study analyzed the impact of reoperation after previous ARR, underscoring that some patients will need reoperation and that timing to reoperation and outcomes depend on indication for reoperation. Valve dysfunction is the primary reason for reoperation with reoperation occurring a median of 6.2 years later and is well-tolerated (low 30-day mortality: 0% and good long-term survival). Patients requiring reoperation for endocarditis/graft infection require reoperation sooner and have greater mortality and worse survival after reoperation. Patients requiring reoperation after index ARR for valve dysfunction most commonly required reoperation for valve dysfunction (67%) (Figure 3).

At time of index root replacement, multiple factors are considered to decrease risk of reoperation, including patient factors such as age, valve pathology, and connective tissue disease. Patients with BAV comprise a large percentage of patients undergoing ARR; 34% of elective ARR in an STS database study[1] and 38% in this study. Mokashi and colleagues[18] and Ouzounian and colleagues[19] found that BAVs can be spared with similar rates of reoperation after VSRR in patients with BAV compared with TAV. However, in this study BAV (HR, 1.76, $P = .009$) was an independent risk factor for reoperation. More than one half (56%) of patients requiring reoperation had a BAV, of whom 55% underwent reoperation for valve dysfunction.

Other important considerations at time of index ARR are the clinical circumstances, for example, whether the procedure was performed in the emergent setting for an acute type A aortic dissection or in the elective setting for aortic insufficiency and root dilation as well as the specific root procedure performed. With the primary goal of a surviving patient at the end of an emergent aortic dissection repair, Bentall procedure remains the gold standard for ARR; however, multiple studies have shown that VSRR can be safely performed in the emergent setting.[4,20] Thirty-five percent of

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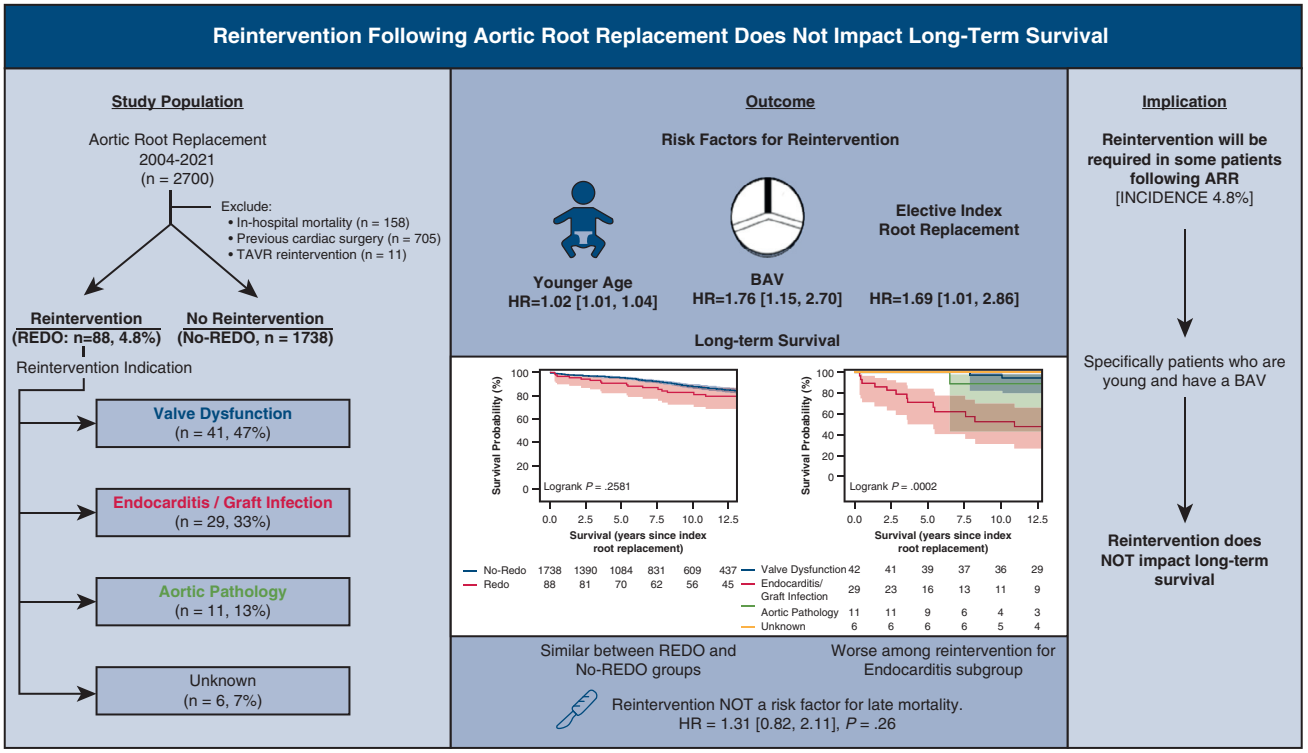

ARR = aortic root replacement; BAV=bicuspid aortic valve.

FIGURE 4. Incidence of reoperation on the aortic valve or proximal aorta after aortic root replacement (*ARR*) was 4.8% and did not impact long-term survival. *TAVR*, Transcatheter aortic valve replacement; *BAV*, bicuspid aortic valve.

patients underwent an urgent/emergent/emergent salvage operation in this study. Surprisingly, the reoperation group underwent more elective ARRs and less urgent ARRs. This observation could be attributable to those undergoing urgent/emergent/emergent salvage operations having worse survival; however, additional investigation is needed in this area. Root procedure at index ARR (VSRR vs bioprosthetic Bentall vs mechanical Bentall vs Ross) depends on patient preference and intraoperative factors in addition to setting. Bioprosthetic Bentall is accompanied by the risk of structural valve degeneration requiring reoperation; mechanical Bentall, life-long anticoagulation, and increased risk of bleeding; and VSRR, durability. Reported reoperation rates are similar between VSRR (1.9%-10.5%) and Bentall (1.5%-15.9%) root replacements.[2,5,6,21-23] In this study, index aortic valve/root procedures were similar between REDO and no-REDO groups, and no specific root procedure was a risk factor for reoperation. With appropriate patient selection, both VSRR and Bentall ARR are suitable options for ARR with a low incidence of reoperation. Younger patients may present for reoperation regardless of index root procedure.

This study is limited by its retrospective nature and the relatively small sample size of patients requiring reoperation. In addition, this study is limited by time selection bias. Both centers in this database have high aortic case volume; therefore, these results may not be generalizable to all practices. Decision regarding type of index root operation was ultimately determined by attending surgeon and influenced by surgeon preference. The 2-academic center database is limited by the varying protocols, operative strategies, and surgeon preferences at the 2 institutions. Index root replacement was a reoperation in more than one quarter of patients; therefore, the REDO group would be at least a third operation. Follow-up was investigated retrospectively; therefore, detection bias may exist.

CONCLUSIONS

Young patients, male patients, and patients with BAVs have an increased risk of reoperation after ARR and reoperation does not hinder long-term survival; however, redo-root replacement does increase risk of late mortality (Figure 4). Reinterventions after ARR are predominantly done for valve dysfunction and are well-tolerated, with low 30-day and late mortality.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: aorta, aortic root replacement, valve-sparing aortic root replacement, aortic dissection, redo-root replacement, reoperation, endocarditis

TABLE E1. Index root replacement outcomes of the entire cohort

Variable	Total (n = 1837)	REDO (n = 99)	No-REDO (n = 1738)	*P* value
Stroke	48 (2.6)	2 (2.3)	46 (2.7)	1.0
Acute renal failure	94 (5.2)	4 (4.6)	90 (5.2)	1.0
Requiring dialysis	50 (2.7)	3 (3.4)	47 (2.7)	.73
Prolonged ventilation	271 (15)	14 (16)	257 (15)	.77
Reoperation for bleeding	103 (5.6)	6 (6.8)	97 (5.6)	.63
Atrial fibrillation	692 (38)	30 (34)	662 (38)	.45
Permanent pacemaker/ICD	65 (3.6)	9 (10)	56 (3.2)	**.003**
Hospital LOS, d	7 (6, 11)	7 (5, 11)	7 (6, 11)	.11

Bold indicates statistical significance ($P < .05$). *ICD*, Implantable cardioverter-defibrillator; *LOS*, length of stay.

TABLE E2. Index root replacement outcomes of the reintervention group

Variable	Reintervention (n = 88)	Valve dysfunction (n = 42)	Endocarditis/ graft infection (n = 29)	Aortic aneurysm/ dissection/ rupture (n = 11)	Unknown (n = 6)	*P* value
Stroke	2 (2.3)	0 (0)	1 (3.5)	1 (9.1)	0 (0)	.23
Acute renal failure	4 (4.6)	1 (2.4)	3 (10)	0 (0)	0 (0)	.51
Requiring dialysis	3 (3.4)	0 (0)	3 (10)	0 (0)	0 (0)	.15
Prolonged ventilation	14 (16)	4 (9.5)	7 (24)	3 (27)	0 (0)	.17
Reoperation for bleeding	6 (6.8)	5 (12)	1 (3.5)	0 (0)	0 (0)	.56
Atrial fibrillation	30 (34)	16 (38)	10 (34)	4 (36)	0 (0)	.35
Permanent pacemaker/ICD	9 (910)	4 (9.5)	3 (10)	2 (18)	0 (0)	.76
Hospital LOS, d	7 (5, 11)	6 (5, 9)	7 (5, 14)	10 (7, 16)	6 (5, 7)	**.03**
Reintervention details						
Time to reintervention, y	3.1 (1.0, 7.9)	6.2 (1.8, 8.9)	1.1 (0.3, 1.7)	3.0 (1.4, 7.0)	8.2 (4.0, 12.4)	**.0001**
AVR	47 (53)	39 (93)	1 (3.5)	1 (9.1)	6 (100)	**<.0001**
Root	36 (41)	4 (9.5)	27 (93)	5 (45)	0 (0)	**<.0001**
Replacement	31 (35)	3 (7.1)	26 (90)	2 (18)	0 (0)	
Repair	5 (5.7)	1 (2.4)	1 (3.5)	3 (27)	0 (0)	
Valve						1.0
Bioprosthetic	57 (88)	36 (88)	19 (86)	2 (100)	0 (0)	
Mechanical	8 (12)	5 (12)	3 (14)	0 (0)	0 (0)	
Valve size, mm	25 (23, 27)	25 (25, 27)	25 (23, 25)	27 (23, 29)		.19
Ascending	26 (31)	5 (12)	14 (48)	7 (64)	0 (0)	**.0002**
Arch	20 (24)	4 (9.5)	11 (38)	5 (45)	0 (0)	**.005**
30-d mortality	5 (5.7)	0 (0)	4 (14)	1 (9.1)	0 (0)	.07

Data are presented as median (25%, 75%) for continuous data and n (%) for categorical data. Bold indicates statistical significance ($P < .05$). *ICD*, Implantable cardioverter-defibrillator; *LOS*, length of stay; *AVR*, aortic valve replacement.

TABLE E3. Risk factors for reintervention

Variable	Univariable HR (95% CI)	*P* value	Multivariable HR (95% CI)	*P* value
Age	0.97 (0.96-0.99)	**.0002**	0.98 (0.96-0.99)	**.0004**
Sex, male	0.54 (0.27-1.08)	.08		
BMI	1.00 (0.97-1.04)	.89		
Diabetes	0.56 (0.23-1.39)	.21		
Dyslipidemia	0.73 (0.47-1.11)	.14		
Hypertension	0.51 (0.34-0.78)	.002		
Chronic lung disease	0.79 (0.36-1.71)	.55		
CKD	0.67 (0.34-1.34)	.26		
Renal failure on dialysis	1.33 (0.19-9.56)	.78		
PVD	0.85 (0.27-2.71)	.79		
CVD	0.91 (0.37-2.24)	.83		
CVA	1.07 (0.26-4.35)	.93		
LVEF	1.00 (0.99-1.02)	.92		
Moderate-severe AI	0.97 (0.63-1.48)	.87		
Connective tissue disease	1.11 (0.41-3.02)	.84		
Bicuspid aortic valve	2.00 (1.31-3.05)	**.001**	1.76 (1.15-2.70)	**.009**
Indication				
Valve dysfunction	1.11 (0.71-1.73)	.66		
Dissection	0.79 (0.35-1.82)	.59		
Aneurysm	0.89 (0.55-1.46)	.66		
Endocarditis	2.97 (0.73,12.09)	.13		
Urgent/emergent/salvage	0.60 (0.36-1.01)	**.05**	0.59 (0.35-0.99)	**.048**
AV repair	1.09 (0.67-1.77)	.73		
VSRR (vs Bentall)	0.94 (0.62-1.44)	.79		
Bioprosthetic Bentall (vs mechanical)	0.96 (0.63-1.46)	.85		

Bold indicates statistical significance ($P < .05$). *HR*, Hazard ratio; *CI*, confidence interval; *BMI*, body mass index; *CKD*, chronic kidney disease; *PVD*, peripheral vascular disease; *CVD*, cerebrovascular disease; *CVA*, cerebrovascular accident; *LVEF*, left ventricular ejection fraction; *AI*, aortic insufficiency; *AV*, aortic valve; *VSRR*, valve-sparing root replacement.

TABLE E4. Risk factors for long-term mortality

Variable	Univariable HR (95% CI)	*P* value	Multivariable HR (95% CI)	*P* value
Age	1.04 (1.03-1.05)	**<.0001**	1.04 (1.02-1.05)	**<.0001**
Sex, male	1.27 (0.91-1.78)	.16		
BMI	1.00 (0.98-1.03)	.94		
Diabetes	2.05 (1.42-2.95)	**.0001**		
Dyslipidemia	1.18 (0.90-1.55)	.24		
Hypertension	2.14 (1.50-3.04)	**<.0001**	1.46 (1.00-2.11)	**.049**
Chronic lung disease	1.71 (1.17-2.51)	**.006**		
CKD	2.55 (1.89-3.45)	**<.0001**	1.59 (1.15-2.20)	**.005**
Renal failure on dialysis	3.74 (1.66-8.43)	**.002**	3.87 (1.68-8.95)	**.002**
PVD	2.25 (1.33-3.83)	**.003**		
CVD	1.06 (0.61-1.88)	.83		
CVA	0.76 (0.24-2.38)	.64		
LVEF	0.98 (0.97-0.99)	**<.0001**	0.98 (0.97-0.99)	<.0001
Moderate-severe AI	1.55 (1.14-2.09)	**.005**	–	–
Connective tissue disease	0.68 (0.30-1.53)	.35		
Bicuspid aortic valve	0.59 (0.44-0.80)	**.0007**	0.65 (0.47-0.90)	**.009**
Indication				
Valve dysfunction	0.51 (0.39-0.67)	**<.0001**	–	–
Dissection	2.50 (1.76-3.56)	**<.0001**	–	–
Aneurysm	1.37 (1.02-1.85)	**.04**	–	–
Endocarditis	0.69 (0.09-4.89)	.71		
Urgent/emergent/salvage	1.79 (1.35-2.40)	**<.0001**	1.78 (1.33-2.39)	**.0001**
AV repair	0.51 (0.34-0.76)	**.0008**	–	–
VSRR (vs Bentall)	0.40 (0.29-0.56)	**<.0001**	0.54 (0.38-0.76)	**.001**
Bioprosthetic Bentall (vs mechanical)	1.10 (0.63-1.90)	.75		
Reoperation	1.31 (0.82-2.11)	.26		
AV reintervention	0.31 (0.11-0.83)	**.02**	–	–
Root reintervention	3.11 (1.80-5.36)	**<.0001**	2.41 (1.17-4.97)	**.02**
Ascending reintervention	3.70 (1.96-7.00)	**<.0001**	–	–
Arch reintervention	4.36 (2.23-8.52)	**<.0001**	–	–
Reintervention for valve dysfunction	0.42 (0.18-0.99)	**0.046**	–	–
Reintervention for endocarditis/graft infection	3.96 (2.25-6.96)	**<.0001**	–	–
Reintervention for aortic aneurysm/dissection/rupture	1.25 (0.34-5.44)	.67		

Bold indicates statistical significance ($P < .05$). *HR*, Hazard ratio; *CI*, confidence interval; *BMI*, body mass index; *CKD*, chronic kidney disease; *PVD*, peripheral vascular disease; *CVD*, cerebrovascular disease; *CVA*, cerebrovascular accident; *LVEF*, left ventricular ejection fraction; *AI*, aortic insufficiency; *AV*, aortic valve; *VSRR*, valve-sparing root replacement.