Operative risks of the Ross procedure

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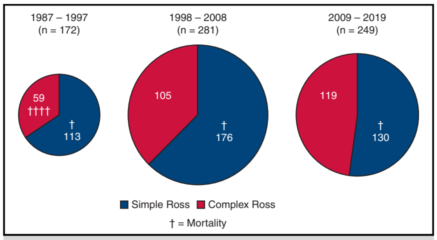
ABSTRACT

Background: The risk of the Ross procedure continues to be debated. We sought to determine the immediate outcomes of the Ross procedure in a large consecutive cohort that included patients undergoing reoperative cardiac surgery and/or concomitant cardiac procedures.

Methods: Between March 1987 and September 2019, 702 patients underwent a full root Ross procedure. There were 530 male patients and 172 female patients, with a mean age of 41.6 years. One hundred and one patients had at least one previous sternotomy; 323 patients had concomitant procedures. Patients were stratified into 2 groups: simple and complex. Simple Ross patients were those who had no previous sternotomy and had only minor concomitant procedures performed at the time of their Ross, such as aortoplasty or closure of patent foramen ovale. The complex Ross group included patients with at least one previous sternotomy and/or additional procedures that we deemed complex, such as ascending aortic replacement and mitral valve repair. Complexity and group outcomes were evaluated in consecutive terciles of time.

Results: There were 7 (1%) operative deaths. Morbidity affected 46 other patients (6.6%). The simple Ross group comprised 419 patients (59.7%), with mortality in 3 (0.7%) and morbidity in 20 (4.8%). The complex Ross comprised 283 patients (40.3%), with mortality in 4 (1.4%) and morbidity in 26 (9.2%). Simple Ross cases decreased in volume over time, with complex cases increasing from 34% to 48%.

Conclusions: Excellent results can be achieved with the Ross procedure despite broader indications that include patients with previous sternotomy and with the need for concomitant procedures. (J Thorac Cardiovasc Surg 2021;161:905-15)



Ross complexity increased while mortality decreased. Ross can be offered to more patients.

CENTRAL MESSAGE

After an initial learning curve, the Ross procedure is safe and can be used in patients with both simple and complex aortic valve disease.

PERSPECTIVE

With appropriate adaptation in experienced hands, the Ross procedure can be performed safely in a broad range of patients with aortic valve disease, including those with dilated or aneurysmal ascending aorta.

See Commentaries on pages 916 and 918.

Although the first pulmonary autograft replacement of the human aortic valve was performed by Donald Ross in 1967,[1] the concept was not applied in the United States until 20 years later. The original subcoronary implant technique was modified to a full root replacement, which became the predominant approach for this operation.[2] The full root replacement Ross operation is longer and more challenging than conventional aortic valve replacement (AVR). Data from The Society of Thoracic Surgeons (STS) database shows that aortic root reconstruction has double the operative mortality of AVR alone,[3] and propensity-matched comparison of Ross versus AVR showed a 3-fold greater risk of mortality with Ross.[4] Recent evidence, however, increasingly supports a long-term survival benefit of the Ross procedure (essentially equivalent to that of a matched normal population) over mechanical and tissue AVR.[5,6] Thus, expanding the eligibility for the Ross procedure would seem desirable, and favorable results were recently reported favorably, with 95 of 261 patients having more challenging clinical presentations.[7] To validate this concept, our study was designed to examine the immediate operative safety of the Ross procedure in a large consecutive series demonstrating progressively broader indications.

METHODS

Patient Population

This case series comprises 702 patients (75% male; mean age 41.6 ± 12.1 years) who had undergone a full root Ross operation performed

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ADULT

Abbreviations and Acronyms

AVR = aortic valve replacement
CABG = coronary artery bypass graft
CTA = computed tomography angiography
ECMO = extracorporeal membrane oxygenation
STS = Society of Thoracic Surgeons
TAVR = transcutaneous aortic valve replacement

by a single surgeon (P.S.) between March 1987 and September 2019. The series includes 17 patients age 4 to 17 years. Bicuspid or unicuspid etiology was documented in 425 of 577 patients (74%). The primary valve dysfunction was aortic stenosis in 337 (48%) and aortic regurgitation in 313 (45%) (Table 1). There were 101 patients (14.4%) who had at least 1 previous sternotomy. A total of 363 additional procedures were performed in 323 patients (46%), most frequently triggered by aneurysmal aortic disease (Table 2). Our Ross database is Institutional Review Board–approved for retrospective analysis without individual patient consent.

Surgical Technique

All patients underwent the Ross procedure using a full root replacement technique, adding increasing levels of neo-aortic root support over time. From the beginning, a measured strip of felt was routinely used to constrain the neo-aortic annulus. By the middle of the series, a second felt strip was routinely added to stabilize the sinotubular junction, and the sinus portion was supported with residual native aortic wall whenever possible.[8] The myocardium was protected with intermittent retrograde cold blood cardioplegia and moderate systemic hypothermia. Cryopreserved pulmonary homograft conduits were used to reconstruct the right ventricular outflow tract in all but 5 patients. Homograft oversizing by 10% was practiced. Since 2008, >99% of homografts have been decellularized homografts. Both aortic and pulmonary reconstructions were completed under a single period of aortic clamping. Continuous technique was used for all suture lines. The upper part of the pericardium was closed over the great vessels whenever possible. Pericardial substitute was used occasionally.

Our approach to the aorta changed over time to prevent progressive aortic and autograft dilatation. Aortas >5 cm in diameter were usually replaced, but lesser degrees of dilatation were often reduced by aortoplasty (Figure 1). The goal was to reduce the diameter to <3.5 cm. Cerebral protection for hypothermic circulatory arrest cases was provided by intermittent retrograde perfusion to both the upper and lower body at a target bladder temperature of 24 °C.[9] Aortic and bicaval cannulation was used in all but 1 case.

Antifibrinolytics were routinely used. Autologous normovolemic hemodilution became routine whenever possible. Maintenance of systolic blood pressure <110 mm Hg was enforced, particularly in the first 24 to 48 hours.

TABLE 1. Patient characteristics by group

Characteristics	Simple (n = 419)	Complex (n = 283)	Total (n = 702)
Female sex	92 (22)	80 (28)	172 (25)
Age, mean ± SD	42.5 ± 11.8	40.5 ± 12.4	41.6 ± 12.1
Age group, n (%)			
<30 y	64 (15)	61 (22)	125 (18)
30 -39 y	103 (25)	75 (27)	178 (25)
40-49 y	126 (30)	75 (27)	201 (29)
≥50 y	126 (30)	72 (25)	198 (28)
Ejection fraction			
n	315	225	540
Mean ± SD	53.2 ± 9.7	53.4 ± 10.7	53.3 ± 10.1
≤35, n (%)	24 (8)	20 (9)	44 (6)
Valve description or morphology			
n	333	244	577
Unicuspid, n (%)*	31 (9)	21 (9)	52 (9)
Bicuspid, n (%)	229 (69)	144 (59)	373 (65)
Rheumatic, n (%)	63 (19)	33 (14)	96 (17)
Other, n (%)	10 (3)	46 (19)	56 (10)
Aortic valve dysfunction, n (%)			
Stenosis	208 (50)	129 (46)	337 (48)
Regurgitation	186 (44)	127 (45)	313 (45)
Other	25 (6)	27 (10)	52 (7)
Prior operations, n (%)			
AVR	—	45 (16)	45 (6)
Valvotomy or repair	—	40 (14)	40 (6)
Other	5 (1)	16 (6)	21 (3)
Endocarditis, n (%)			
Active	—	18 (6)	18 (3)
Healed	20 (5)	25 (9)	45 (6)

SD, Standard deviation; *AVR*, aortic valve replacement. *Includes 4 quadricuspid valves.

TABLE 2. Operative characteristics and outcomes of patients by group

Characteristics	Simple (n = 419)	Complex (n = 283)	Total (n = 702)
Cross-clamping, n	351	254	605
Cross-clamp time, min, mean ± SD	170 ± 38.0	201.3 ± 43.3	183.5 ± 43.0
CPBT, n	348	253	601
CPBT, min, mean ± SD	208 ± 49.6	245.8 ± 55.2	224.1 ± 55.4
Concomitant procedures, n (%)			
Total	98	265	363
Ascending aortic graft	—	83 (29)	83 (12)
Aortoplasty	85 (20)	26 (9)	111 (15)
Mitral	—	44 (16)	44 (6)
Tricuspid	—	7 (2)	7 (1)
Mitral + tricuspid*	—	8 (3)	8 (1)
Septal	—	28 (10)	28 (4)
CABG	—	33 (12)	33 (5)
Other	13 (3)	36 (13)	49 (7)
Transfusions, n	320	236	556
Patients transfused, n (%)	47 (15)	81 (34)	128 (23)
Autograft regurgitation, n (%)†	303	247	550
None/trivial	220 (73)	175 (71)	395 (72)
Mild	77 (25)	68 (28)	145 (26)
Moderate	5 (2)	3 (1)	8 (1)
Severe	1 (<1)	1 (<1)	2 (<1)

SD, Standard deviation; *CPBT*, cardiopulmonary bypass time; *CABG*, coronary artery bypass grafting. *M + T: Both mitral and tricuspid repair. †Autograft function on transthoracic echocardiography before discharge.

Beta-blockers were started early and continued for 3 to 6 months. Additional agents were used as required. Anti-inflammatory agents were prescribed for 1 to 3 months until decellularized homografts became routine. Aspirin was optional.

Previous Operations

Of the 101 patients with a previous sternotomy, 85 (84%) were aortic valve operations, including replacement, repair, and open valvuloplasty. Of the 45 replacements, most were tissue valves, but 8 were mechanical valves and 5 involves previous aortic homografts, 4 as full root replacements. Most patients had only 1 previous sternotomy, but 11 (11%) had 2 or more. Central cannulation was used in all but 1 of these patients.

Concomitant Procedures

Of the 323 patients with concomitant procedures 55 (17%) had prior sternotomy. Replacement (83) or repair (111) of the ascending aorta were most common additional procedures. Mitral (52), coronary (33), and septal (28) procedures were less common.

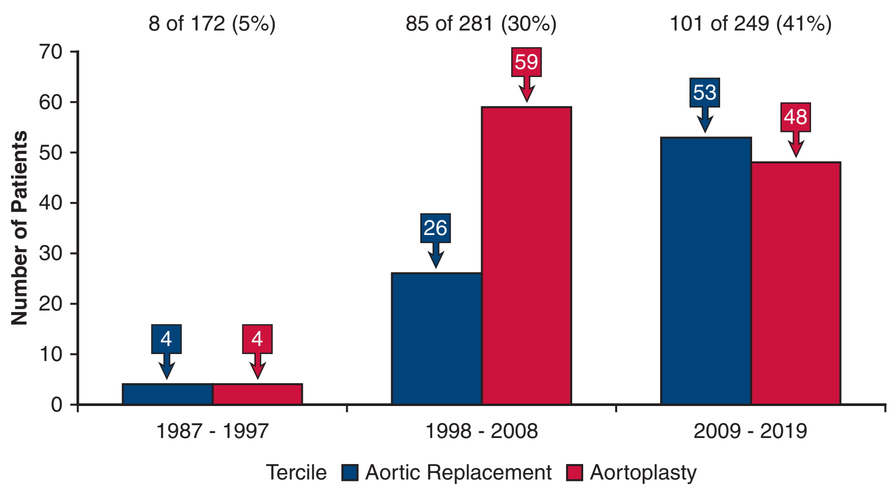


FIGURE 1. Increasing intervention on the ascending aorta over time. Aortic dilatation was more aggressively addressed after the first decade. Replacement of the ascending limb is used more than aortoplasty, but aortoplasty is still used for lesser degrees of dilatation, especially in younger patients to preserve elasticity.

Group Stratification

The patients were divided into 2 groups, simple Ross and complex Ross (Table 1). Patients undergoing straightforward concomitant procedures, such as aortoplasty and patent foramen ovale or atrial septal defect closure, were included in the simple Ross category. Patients who had undergone previous sternotomy were classified as complex Ross, as were those with active endocarditis and those with major concomitant procedures, such as ascending aortic replacements and mitral valve repair. The simple Ross group comprised 419 patients 419 (59.7%); the complex Ross group, 283 (40.3%).

Temporal Perspective

The series was divided into 3 consecutive terciles each approximately 1 decade long (1987-1997, 1998-2008, and 2009-2019). Trends in results were compared between groups in each decade (Figure 2 and Table E1).

Statistical Analysis

Because this was a single-surgeon case series, no sample size or statistical power calculations were performed. Data were reported through descriptive statistics, with no hypothesis testing. Ordinal and nominal data were expressed as absolute and relative frequencies. Continuous data were presented as mean ± standard deviation. Mortality and morbidity data were tabulated into 2 group stratifications as described above and also further subdivided into 3 terciles of time. Trends in mortality and morbidity over time were assessed descriptively. Mortality was tracked at postoperative follow-up appointments routinely scheduled for >30 days after operation.

RESULTS

Complexity of Cases

The proportion of simple Ross cases decreased from 68% to 63% to 52% over the terciles of time, while complex Ross cases increased from 34% to 37% to 48% (Figure 3). The majority (85%) of previous operations were on the aortic valve (Table 1). Ninety-eight "simple" concomitant procedures were performed in the simple Ross group, most often aortoplasty, which was done in 85 patients (20%). Two hundred sixty-five patients in the complex Ross group had more extensive additional procedures, including ascending aortic replacement in 83 (29%) and mitral valve repair in 50 (20%) (Table 2).

Overall, the mean clamp time was 183.5 ± 43 minutes (median, 193 minutes; range, 110-405 minutes). The mean pump time was 224.1 ± 55.4 minutes (median, 230 minutes; range, 135-471 minutes). The times were understandably longer (by approximately 20%) for the cohort of complex Ross patients (Table 2).

For the 74 patients requiring hemiarch aortic replacement, circulatory arrest times ranged from 13 to 34 minutes (mean, 22 minutes) (Figure E1).

Mortality

The 30 day all-cause mortality was 1% (n = 7). There were 3 deaths among the 419 patients (0.7%) in the simple Ross cohort, and 4 deaths in 283 patients (1.4%) in the complex Ross cohort. Five of the 7 deaths (71%) occurred during the first one-third of the experience. There was 1 death in each subsequent tercile (Figures 2 and 3). The first 2 deaths were due to coagulopathic bleeding in the setting of active aortic valve endocarditis. Right ventricular failure, most likely due to right coronary button compromise, caused the next 2 deaths. The last 3 deaths were caused by late postoperative bleeding from the right ventricular outflow tract, nosocomial pneumonia, and sudden unexplained refractory ventricular fibrillation occurring on day of discharge in 1 patient each. Figure 4 shows the rapid decrease in mortality early in the series contrasted to the trend line for complexity increasing over time.

Morbidity

Overall, 46 of the remaining patients (6.6%) had a significant morbidity (Table 3). This affected 20 of 419

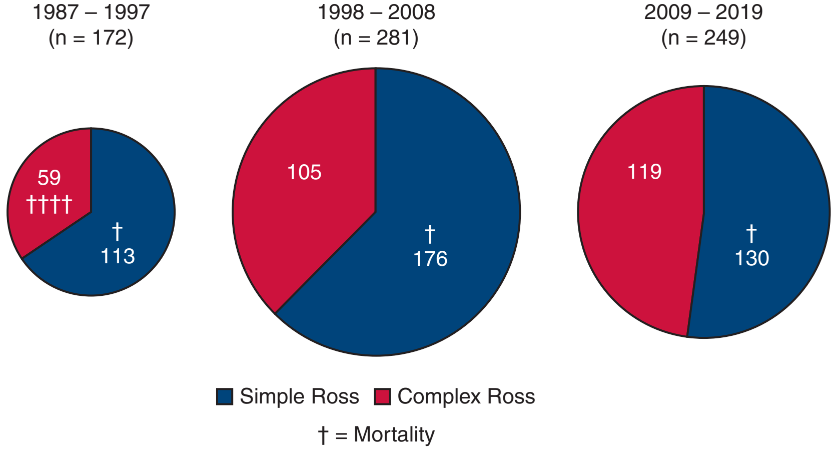


FIGURE 2. Ross complexity and mortality over time. After a learning curve, operative mortality for the Ross procedure fell to a very low level and remained so while the proportion of more challenging cases steadily increased. Complex cases included Ross in the setting of reoperative sternotomy, active endocarditis, ascending aortic replacement, mitral valve repair, coronary bypass grafting, or a combination of these. Each mortality is indicated by a "tombstone" cross. These were highly localized to complex cases done early in the experience so that 485 survivors stood between the last two deaths.

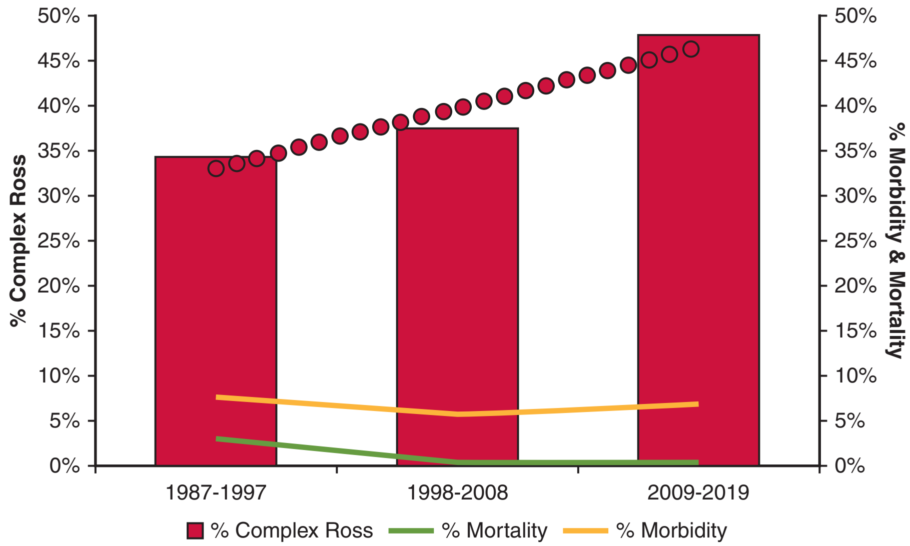


FIGURE 3. Temporal relationship of Ross complexity, mortality, and morbidity. The size of the bars indicates the percentage of complex Ross increasing over time. The decreasing mortality (*green*) and morbidity (*yellow*) trends are shown based on percent of all patients both simple Ross and complex Ross over 32 years. Over the last 2 decades, nearly 50% have been complex cases, yet mortality is <1% and morbidity is <7%.

patients (4.8%) in the simple Ross group and 26 of 283 (9.2%) in the complex Ross group (Figure 3). Over time, there was a trend toward decreasing morbidity in the complex Ross patients through the 3 terciles: 11.9%, 8.6%, and 8.4%, respectively. For the simple Ross patients, morbidity remained low over time: 5.3%, 4.0%, and 5.4% (Table E1). The 5 patients requiring mechanical support (all for <1 week) included 2 with an aortic balloon pump, 2 with a right ventricular assist device, and 1 with extracorporeal membrane oxygenation (ECMO) due to a stenotic left main button that was stented the next morning with recovery of left ventricular function. Rescue vein grafts were required to correct 1 other left and 2 right button problems. Reoperation for bleeding was required for only 6 patients. Just 23% of patients needed blood or blood products. Reoperation was also required in 2 other patients. One required release of overzealous pericardial closure causing tamponade physiology, performed on the day after surgery. The other required mitral valve replacement for severe residual

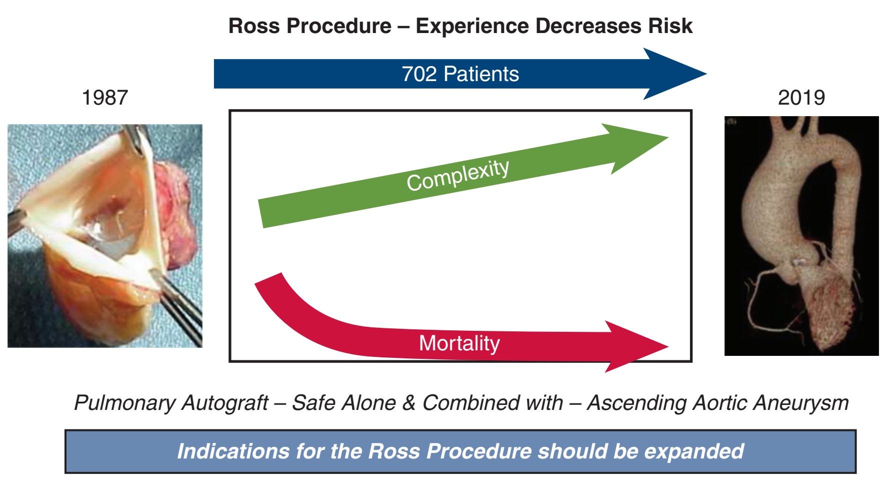


FIGURE 4. Ross procedure; experience decreases risk. The use of the delicate pulmonary autograft to replace the diseased aortic valve can be done safely. There has been only 1 death since 1998. As experience was gained, indications were broadened to include more complex cases, including those with ascending aortic aneurysm, mitral regurgitation, and coronary disease. Patients with previous sternotomies were also considered complex in this series of Ross procedures.

TABLE 3. Mortality and morbidity by patient group

Complication*	Simple (n = 419)	Complex (n = 283)	Total (n = 702)
Mortality, n (%)	3 (0.7)	4 (1.4)	7 (1.0)
Morbidity, n (%)			
Reoperation for bleeding	4 (1.0)	2 (0.7)	6 (0.9)
Other reoperation	1 (0.2)	1 (0.4)	2 (0.3)
Mechanical support†	1 (0.2)	4 (1.4)	5 (0.7)
Rescue CABG	2 (0.5)	1 (0.4)	3 (0.4)
Stroke, n (%)‡	1 (0.2)	4 (1.4)	5 (0.7)
Right ventricular dysfunction, n (%)§	3 (0.7)	2 (0.7)	5 (0.7)
Renal failure, n (%)‖	1 (0.2)	5 (1.8)	6 (0.9)
Myocardial infarction, n (%)	1 (0.2)	0	1 (0.1)
Respiratory failure, n (%)¶	3 (0.7)	3 (1.1)	6 (0.9)
Permanent pacemaker, n (%)	2 (0.5)	3 (1.1)	5 (0.7)
Deep sternal infection, n (%)	1 (0.2)	1 (0.4)	2 (0.3)
Total patients with morbidity, n (%)	20 (4.8)	26 (9.2)	46 (6.6)
Total with either morbidity or mortality, n (%)	23 (5.5)	30 (10.6)	53 (7.5)

CABG, Coronary artery bypass grafting. *Complications are listed in decreasing order of author-designed priority. Patients with multiple complications are listed only once (under the highest priority category). †Mechanical support: extracorporeal membrane oxygenation (n = 1), right ventricular assist device (n = 2); and balloon pump (n = 2). ‡Stroke defined as new cerebral imaging defect and/or persistent neurologic defect beyond 48 h. §Right ventricular dysfunction requiring inotropic support beyond 48 h. ‖Renal failure: acute kidney injury requiring temporary dialysis. (One case was persistent.) ¶Respiratory failure: ventilator support over 24 h (One patient needed temporary tracheostomy.)

rheumatic subvalvular stenosis at 3 days after Ross with mitral repair. Five patients sustained a stroke, only 1 of whom had circulatory arrest, who was among the 4 with full recovery.

Discharge Echo

Routine echocardiography was performed before discharge, but results from the early part of the series are not available. More than 70% showed trivial or no autograft regurgitation, 26% had mild regurgitation, and only 1% had moderate regurgitation. Two patients were classified as severe (Table 2). Stenosis of the autograft has never happened. Early function of the pulmonary homograft was typically so normal that the official report did not mention that valve. Very mild pulmonary regurgitation was common, but peak gradients >10 mm Hg were very rare.

DISCUSSION

In the 50 years since Donald Ross first published his work with the pulmonary autograft,[1] its use has been limited or eliminated from the treatment options available to many young patients with aortic valve disease. This has been due in part to progress in valve repair with regurgitation as the primary pathology, but mostly to the ease and safety of doing simpler operations using mechanical or animal tissue valve replacement. This trend was driven by concerns regarding the technical complexity and longer ischemic time of the Ross. In the STS database analysis by Reece and colleagues,[4] a Ross operative mortality rate of 2.6% was considered prohibitively high and determined to be "unacceptable," because significantly less risky alternatives were available. A key limitation of that study was that one-half of the cases were treated in centers averaging fewer than 2 cases per year.

For conventional AVR alternatives, long-term "excess mortality" has been well documented in recipients of tissue valves,[10] and recipients of mechanical valves have life-long concerns with bleeding and thromboembolic consequences. However, the Ross procedure has demonstrated potential for restoration of normal life expectancy.[6,11,12] Even if slightly less than normal at 20 years, there is a notable survival advantage over the alternatives.[13]

Therefore, with the emergence of the Ross as the best long-term option for young adults, it would seem logical to broaden the indications for this procedure. The safety of this concept needs confirmation, which we sought to provide by examining 30-day outcomes in a consecutive case series including both simple and complex Ross procedures. Our technique evolved to downsize and stabilize any dilated aortic annulus or sinotubular junction, striving to make the operation applicable in complex patients, importantly including patients with ascending aortic disease. Modestly longer ischemic and perfusion times did not increase mortality or morbidity.

The learning curve at the beginning of this series was significant.[14] Mortality dropped rapidly, resulting in only 1 death since 1998. In retrospect, a lack of experience in patient selection and technical skills led to the first 2 deaths, 1 with native valve endocarditis and the other with prosthetic valve endocarditis very early in our series. Subsequent patients with native valve endocarditis have been treated successfully using the Ross, but prosthetic valve endocarditis and major root destruction were consistently treated with other techniques. Two other early mortalities were due to our inability to recognize and deal with coronary and functional impairments of the right ventricle. Higher implantation of the right coronary (distal to the autograft in native aorta in 8 patients) and the option of temporary right ventricular assist device rescue have changed that picture.

In addition to sustaining the low mortality rate after the learning curve, morbidity also trended downward through the first decade and has been maintained at a low level despite a slight trend upward in the simple group. Experience has led to technical refinement, improved patient selection, and rescue capability which moved patients from mortality to morbidity. Upward trends in combined freedom from either mortality or morbidity were demonstrated over time (Figure E2). Safety appears to have been established and maintained. Furthermore, these outcomes (overall 1% mortality and 6.6% morbidity) including all patients in our 32 year experience compare favorably to mortality (1.6%) and morbidity (16%) in young and middle age adults undergoing isolated mechanical or bioprosthetic AVR between 2013 and 2018.[15]

Just how far can the indications be expanded? A life expectancy of at least 15 to 20 years is required for a patient to be considered for the Ross option. That translates to healthy people up to approximately age 60. Any type of valve morphology can be accommodated with the full root Ross technique, including the Sievers type 0.[16] The Ross should not be done in patients with such conditions as renal failure, genetic connective tissue diseases, and acute aortic dissection. We did push the envelope to include, for example, selected patients with rheumatoid arthritis, anomalous coronary origin, bicuspid pulmonary valve, and radiation for Hodgkin lymphoma. A patient with regurgitant triple-valve disease and an ejection fraction of 30% had a Ross along with mitral and tricuspid rings and a papillary muscle sling. On the other hand, a 27-year-old with 5 previous sternotomies and total calcification of both a homograft root and the entire left ventricular outflow tract was not accepted for a Ross. Transcutaneous aortic valve replacement (TAVR) was done successfully.

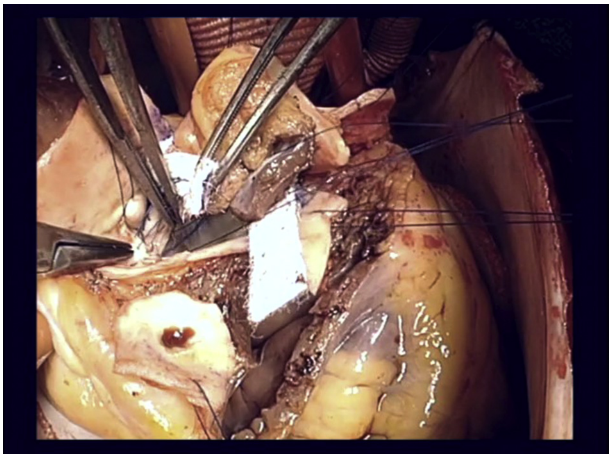
Indeed, TAVR has become a prominent feature of conversations with patients who are attracted by the fast recovery that follows those procedures. Although the appeal is understandable, a recent look at STS data (2013-2018) shows that TAVR, tissue, and mechanical aortic valve replacements in patients age 18 to 55 years each had a 30-day mortality rate >3%, whereas mortality for the Ross in this age group was only 0.7%.[15] Amazingly, despite our total lack of long-term data in this age group and with a high incidence of bicuspid morphology, 1% of patients were treated with TAVR, compared with only 0.6% with Ross, and the use of TAVR was rising rapidly. Another recent study showed considerable hazard using TAVR in bicuspid valves.[17] Those with the highest calcification burden had a 2-year mortality rate of 25.7%. The average patient age in that study was 74.7 years, which limits comparisons, but these findings should be seriously considered when evaluating the use of TAVR in young people who are candidates for Ross, the vast majority of whom have bicuspid valves. The use of tissue aortic valves continues to increase, while the use of mechanical valves declines. Many cardiologists believe that tissue valve degeneration is no longer a problem because we now have valve-in-valve TAVR; unfortunately, there are no data to support a strategy of first tissue AVR, then TAVR (or vice versa) in young patients like those described in our series.

Insights

Considerable insights have come from this long experience. Patient selection emphasizes life expectancy and quality of life, as well as genetic and anatomic factors. Transthoracic echocardiogram and computed tomography angiography (CTA) of the chest usually provide excellent anatomical and functional detail so that cardiac catheterization is rarely needed. CTA is particularly helpful before reoperative sternotomy. Aortic valve repair should be encouraged whenever possible in young patients with isolated regurgitation, but Ross is the alternative when a durable repair cannot be anticipated. Concomitant disease should be treated with durable and "nonthrombogenic" techniques such as mitral valve repair and arterial bypass grafts.

Aortic tissue quality and length, as well as diameter and age, should be considered when choosing replacement or aortoplasty. Among patients with a dilated aorta, the aortic annulus was smaller in those with stenosis compared with those with regurgitation, but annulus size did not predict the choice of aortic treatment (Figure E3). Aortic size was the most important factor in choosing between replacement and aortoplasty (Figure E4). We speculate that preserving the native aortic wall at a smaller diameter will both reduce the wall tension and maintain the capacitance chamber effect, thereby decreasing afterload stress on the autograft root. Therefore, we tend to use aortoplasty more in the younger aorta that will need its intrinsic elasticity longer than the older aorta. We have never had to reoperate on a patient because of an aorta that was treated in either manner.

Supporting the autograft root at the annulus and the sinotubular junction is especially important in the patients with aortic regurgitation and those with a dilated ascending aorta. This can be done in multiple ways, but we believe that support has reduced the incidence of autograft dysfunction and need for reoperation (Video 1). These modifications make Ross root replacement reasonable in the setting of a dilated annulus, root, or ascending aorta.



VIDEO 1. Ross procedure: lessons learned and technical details of current technique. Technical aspects of key elements are presented, including autograft harvest, proximal and distal autograft suture lines with felt support, inclusion of native aortic wall for sinus support, aortic replacement, aortoplasty, and external root support. Examples of late follow-up imaging are also included. Video available at: https://www.jtcvs.org/article/S0022-5223(20)33338-9/fulltext.

We recommend tight blood pressure control, preferably with beta-blockers, early after surgery and for 6 to 12 months thereafter to allow the autograft to adapt to systemic pressure. Follow-up echocardiography should be obtained annually, and it is reasonable to perform CTA at 5-year intervals. Dental prophylaxis should be provided, even though endocarditis is rare. We know of 7 patients in this series who have had endocarditis, 4 on the homograft side. Antibiotic success is similar to that in native valve endocarditis. The finding of isolated autograft root dilatation without valve dysfunction should not cause a rush to reoperation even if dimensions of 5 to 5.5 cm are observed, because these roots have never been reported to rupture.

Finally, we learned that this operation can be taught and learned, but this is not a simple proposition. Solid experience with other types of aortic root surgery is a requirement. Harvesting the autograft from the right ventricular outflow tract is unique to the Ross but is reproducible. The proximal autograft suture line is the most important part of the operation and requires 3-dimensional thinking. The function of the neoaortic valve is totally dependent on fully maintaining the natural geometry of the pulmonary valve as it is implanted into the root. The delicate pulmonary artery tissue must be handled much more gently than a prosthetic graft, and sutures must be placed precisely. Speed is never superior to accuracy. Approximately 20 to 25 cases within 3 to 5 years can ensure competence, but 75 to 100 cases are required to achieve expertise. Our recommendation is that the best setting for Ross training is at the attending level with joint participation of senior and junior people in a center of excellence.

Limitations

The primary strength of this case series is that it covers a long time frame with significant volume by a single surgeon who personally recorded the data at the time of surgery and during postoperative visits. It includes a large number of patients who had undergone more than an isolated Ross as indications were broadened over time. By including the very first cases in a consecutive series, we demonstrated that experience matters and is a major factor that allows the broadening of indications without increasing risk. On the other hand, there are important limitations that are inherent in case series as a study design. There was no explicit control or comparison group. With no formulated hypothesis or sample size, no statistical power calculations could be performed; therefore, our conclusions and assessment of outcomes were predicated on descriptive statistics and observed trends. The case series design also limits the generalizability of the outcomes. Nonetheless, we have shown that a 30-day mortality of <1% is achievable.

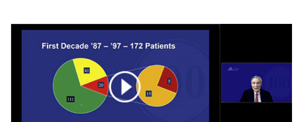
Long-term follow up was not the purpose of this study, and is clearly needed to confirm the ultimate benefit of the Ross procedure in this expanded indication pool. Immediate postoperative echocardiography results were excellent, although data are incomplete and subsequent echocardiography data are difficult to obtain in significant numbers. For the first 461 patients in our series, we reported a 15-year survival of 93%.[18] The Social Security death index was not reinterrogated, because our focus was on acute outcomes for this study. The benefits seen in many of these patients now in their third decade after surgery is what motivates making it available to more patients.

CONCLUSIONS

Excellent early outcomes can be achieved with the Ross procedure even when indications are expanded to include patients with previous sternotomies and when concomitant procedures are required. This should encourage centers with experience to offer more patients the option of the Ross procedure even when aortic valve disease is not an isolated problem.

Webcast

You can watch a Webcast of this AATS meeting presentation by going to: https://aats.blob.core.windows.net/media/20AM/Presentations/Thirty-Two%20Years%20and%20702%20Ross%20Proced.mp4.



Conflict of Interest Statement
The authors reported no conflicts of interest.

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Key Words: Ross procedure, pulmonary autograft, aortic root replacement

Discussion

Presenter: Dr Paul Stelzer

Dr Joseph S. Coselli *(Houston, Tex)*. Dr Stelzer, you are to be congratulated for bringing us up to date on your truly extensive experience with the Ross operation extending over 3 decades. You mentioned the STS database, and as you well know, it's not a popular operation for valve replacement in the STS database. The Ross procedure has garnered variable enthusiasm over the years.

In your series of 702 patients, you encountered a rather notable low operative mortality rate (<1%). Although remarkable, it's not too dissimilar from a recent report by Tirone David on 212 consecutive patients undergoing the Ross operation, where he encountered only 1 death.

Recently in several publications, both you and others have shown truly excellent early results, particularly in younger patients who are undergoing this procedure for aortic valve pathology. When compared to alternative approaches for valve replacement (such as mechanical, biological with either stented or stentless valves, and homograft options) the Ross operation has a lower incidence of bleeding complications, thromboembolism, endocarditis, and, very importantly, in some series, a long-term survival rate that closely approximates the normal population.

However, there is a concern that the Ross procedure turns a single-valve operation into a double-valve operation, and as a consequence, overall complexity is increased. I have a few scenarios I'd like you to comment on further. Although this presentation is primarily on the early results, I wonder if you could comment, at least somewhat, on your long-term survival and reoperation.

For instance, as you well know, the Achilles heel of this operation is not only its increased complexity at the initial procedure, but also concerns regarding long-term survival both with and without reoperation. This was highlighted in a recent publication in *Circulation: Cardiovascular Quality and Outcomes* by Etnel and colleagues in Rotterdam (Etnel J, Huygens S, Grashuis P, Papageorgiou G, Roos Hesselink J,Bogers A, et al. Bioprosthetic aortic valve replacement in nonelderly adults. A systematic review, meta analysis, and microsimulation. *Circ Cardiovasc Qual Outcomes*. 2019;12:e005481), where they looked at 99 publications and over 13,000 patients and pointed out that an important drawback of the Ross procedure was late structural valve deterioration of both the autograft and the valve substitute within the right ventricular outflow tract.

Additionally, Etnel and coauthors found that reintervention rates were highly age-dependent. The lifetime risk of autograph reintervention ranges from 94% in children to 32% for 55-year-olds. For the right ventricular outflow tract conduit, the lifetime reintervention rate was 100% in children and 14% in 55-year-olds. Importantly, this operation is primarily (in most series) focused on patients in a younger age group.

Of course, the importance of your current experience really lies in the broadening of traditional indications to include patients with endocarditis, prior sternotomy, and concomitant operations. Clearly, over 30 years, you've developed extensive technical skill, and I wonder if you might share your thoughts on annular stabilization. What technique do you use? When do you use it? Do you modify the operation for bicuspid pulmonary valves? And certainly, you've had to reoperate on patients who had failed Ross operations. Where do you think the aortic valve-sparing techniques described by Tirone David fit in? Finally, because many of your patients have bicuspid valves and ascending aortic aneurysms, what are your criteria for concomitant repair with the ascending aorta? And, would you use a Dacron graft to replace this section or instead perform aortoplasty? As pertains to the aortic diameter, where's your threshold cutoff (4, 4.5, or 5 cm)? And again, thanks for your amazing contribution. Excellent results and a wonderful presentation.

Dr Paul Stelzer *(New York, NY)*. Thank you very much, Joe, for your comments. These are good questions. I think you really hit the nail on the head that this is a more complex procedure. It takes longer to do, and you have to have a great deal of patience to go about doing these operations. Don't be in a big hurry; learn how to protect the heart and also learn how to be more selective when you start doing these operations—and then add the more complex things. Sometimes you don't have a lot of choice, but again, fundamental skills in other aortic surgery before you try to do this is key; for example. an aortic homograft root replacement is a "training wheels" Ross. It takes time to get the hang of it.

As to your comments about the double-valve complexity: Yes, it is more complex, but putting a homograft to the right side is something that you can get the hang of, and that's not the more difficult part of the procedure. That holds true, but commenting on the long-term, I thought the problem was going to be the homograft, and it's not.

I've done fewer than 20 reinterventions in this whole time. Fewer than 20 patients this whole time in my series that I know about have had anything done to that homograft. The left side, on the other hand, that was a problem. But it took me over a decade to realize that the ascending aorta could dilate. And in fact, it wasn't just the ascending aorta; it was the autograft—we left too much of the original pulmonary artery behind, and we didn't stabilize the sinotubular junction.

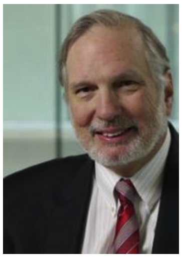
You asked about stabilizing the annulus, and yes, that's important, and I do that every single time, and I make sure that the autograft dictates the new diameter of the aortic annulus by circling that with a little Teflon felt. But I should have done that to the sinotubular junction as well. As Tirone David says, if you stabilize the sinotubular junction and the annulus, and the valve function is good, it's going to stay that way no matter what happens to the sinus portion. But the cardiologists get a little nervous about the root looking bigger. When it gets to 5 cm, they freak out and say you have to reoperate. I've never seen one rupture. I've seen a couple of localized dissections in the noncoronary sinus, and the one I let get the biggest was 7.5 cm, at which point he had moderate aortic regurgitation, so I re-replaced his aortic root.

You are correct to remind us that the ascending aorta itself can dilate, and so you asked about the threshold for intervening on that at the initial procedure. My principle is: I don't want anybody to leave the OR with an aorta bigger than 3.5 cm. So if it's between 3.5 and 4.5 cm, I'll do a plication. I'll bring it down to less than 3.5. If it's 5 cm, it's going to get replaced, and I'm not going to cheat just to save circulatory arrest by leaving a 4.5-cm segment proximal to the arch. I'll just go right smack-dab into the hemiarch and do the whole thing—get rid of that tissue. If the aorta is between 4.5 and 5 cm, that's where I evaluate the tissue. If the tissue is really thin, replace the thing. If the tissue is good quality, go ahead and plicate that. The younger the patient, the more likely I am to choose plication to preserve flexibility.

Valve sparing for redo operations: yes, if you can do so, that would be a reason to go back sooner rather than later. If you think you're not going to be able to spare the valve, then wait as long as you can until the patient is symptomatic. Cardiologists are always hot to reoperate on somebody with aortic regurgitation who's asymptomatic. But why? They don't want to operate in the first place until symptoms or the ventricle trigger the need for surgery.

But anyway, when you do reoperate, try to spare that living valve. I think that living valve is a major part of the secret to the long-term success of the Ross operation; you want to preserve that if you can. The question was asked about how many of these reops I have done. I'll have to say conservatively, I've done 65 of them. I did not do the original Ross in all of these. There were some that Ron Elkins had done in Oklahoma and that came to see me after he retired.

In about half of them, I was able to save the autograft. In the other half, I replaced it. But it's a difficult operation, and there are principles. One is: never try to get between the autograft and the homograft, especially before you have a cross-clamp on. Don't try to develop that plane. There is usually a spot right up high underneath the proximal belly of the arch, right where the aorta turns the corner into the arch. You can get into that plane in most redo cases very easily. Put your clamp up there and try not to mess with that space between the autograft and homograft. That's how you get into trouble.



Dr Joseph E. Bavaria *(Philadelphia, Pa)*. Paul, nice presentation. Could you elaborate on how you approach the patient? Because the bottom line is, you have an STS score of less than 1 for most of these patients, and you just stated that you had a 7.5% major complication and death risk in these patients. It seems to me that the STS total score would be quite a bit less than that. And in this day of TAVR, where say you have a 40-year-old guy who could be a Ross candidate, you put in one of these brand-new tissue valves and it's going to be a 15-year valve, plus you're going to add an extra 8 to 10 years if you get a big valve in any way with a TAVR. Really what you've got is a 20- to 25-year biological construct, and then you do a redo at 65, and a lot of us on this panel, anyway, can do a redo AVR with less than a 1% mortality rate. So how do you talk to your patients about that option versus a Ross procedure?

Dr Stelzer. That's a good question, and certainly the decrease in older patients that we saw in the last decade was because we thought we don't have to do this operation in people over 50 anymore—we're going to be able to put in tissue valves and then rescue those with TAVR. Driving that down into the 40s, it's a little bit harder for me to believe that's going to happen.

And a lot of these patients don't have a big annulus (especially the young women with stenosis); you're not going to get a big valve in there. And that's a big problem. Those are the ones that really benefit greatly from the hemodynamic efficiency of the Ross. So you need to get a good-sized valve in if you're not going to do a Ross. And you have to really be a believer in this valve-in-valve stuff. At this point they call 3-year follow-up on valve-in-valve "long-term" results—you gotta be kidding me.

So I think the other side of the age coin is that if you if you take somebody and you do a Ross on them when they're 50, they may never need another operation. In the recurrence rates paper that Dr. Coselli is talking about, certainly the lowest reoperation rates were in the older patients who had a Ross. That's it. Talk about "one and done," like we used to say for mechanicals. Maybe it's better to present it that way when offering a Ross to a 50-year-old.

It's always been ironic to me that people believe in doing the Ross for kids but not for young adults. But it's the kids that are all going to have to get redos for their homografts because they outgrow them. This has been well documented, and they have a high likelihood of living long enough to develop this complication. I think that's part of the advantages/disadvantages of the operation. You have very good long-term survival, so you have a high likelihood of needing further intervention—but you won't need a reoperation if you're not alive to have it.

ADULT

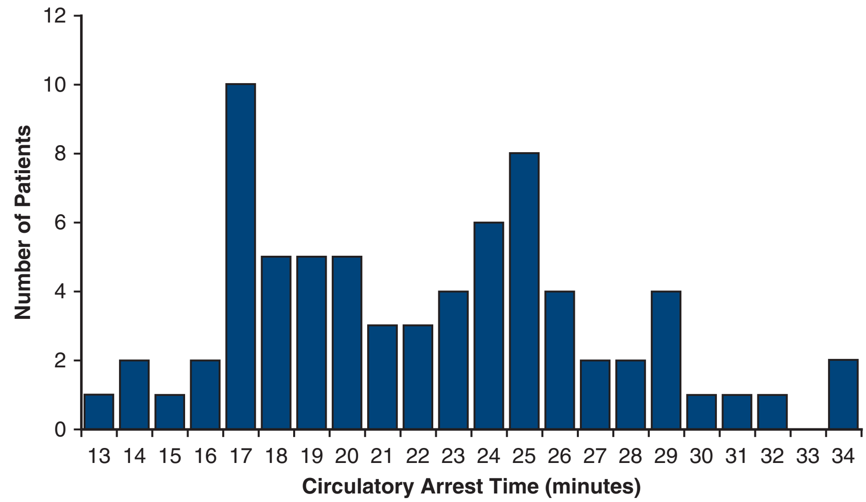


FIGURE E1. Duration of circulatory arrest. Aortic replacement in 74 patients was done under circulatory arrest, the duration of which is depicted in minutes on the *x*-axis. Most times were between 17 and 29 minutes. Cerebral protection was intermittent retrograde perfusion. Longest times were in patients requiring separate arch branch grafting.

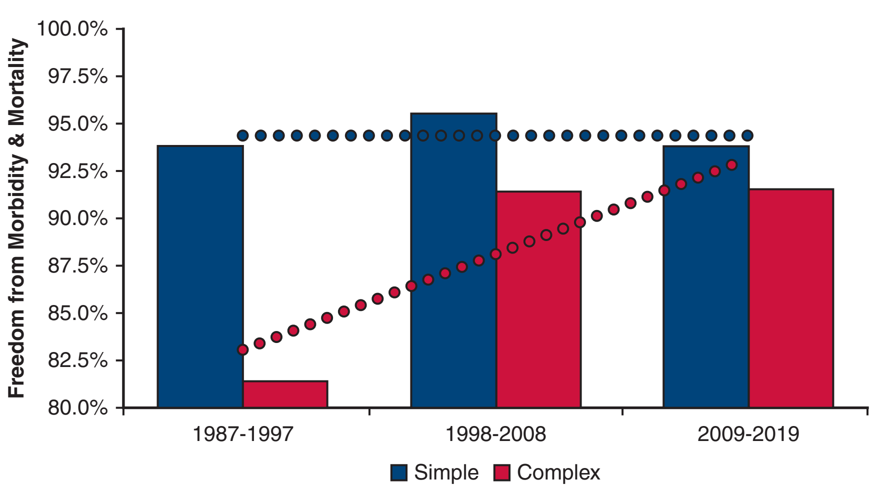


FIGURE E2. Percent freedom from both morbidity and mortality. Freedom from either morbidity or mortality is shown. The separation of the simple and complex groups shows that the trend for improvement in outcomes was almost completely explained by better outcomes in the complex Ross patients. Risk of simple Ross started low and remained so. The small number of events that influence these trends are shown in Table 3 and expanded further in Table E1.

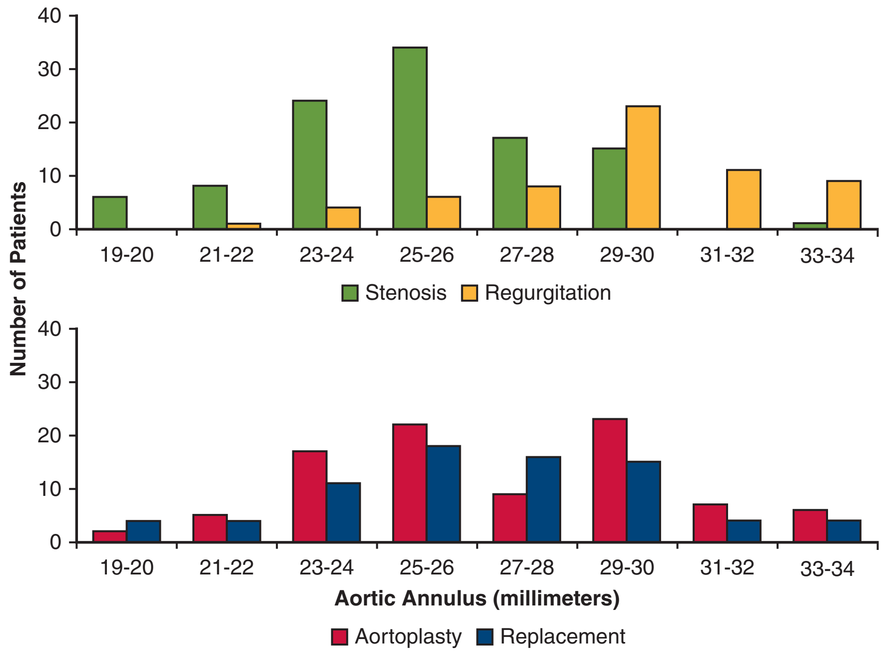


FIGURE E3. Aortic annulus size relation to valve dysfunction and aortic treatment. Annular dilatation was greater in patients with aortic regurgitation than in those with aortic stenosis, but annular size bore no relation to the choice of replacement or repair of the ascending aorta. Note that only patients who received aortoplasty or aortic replacement are included in this figure.

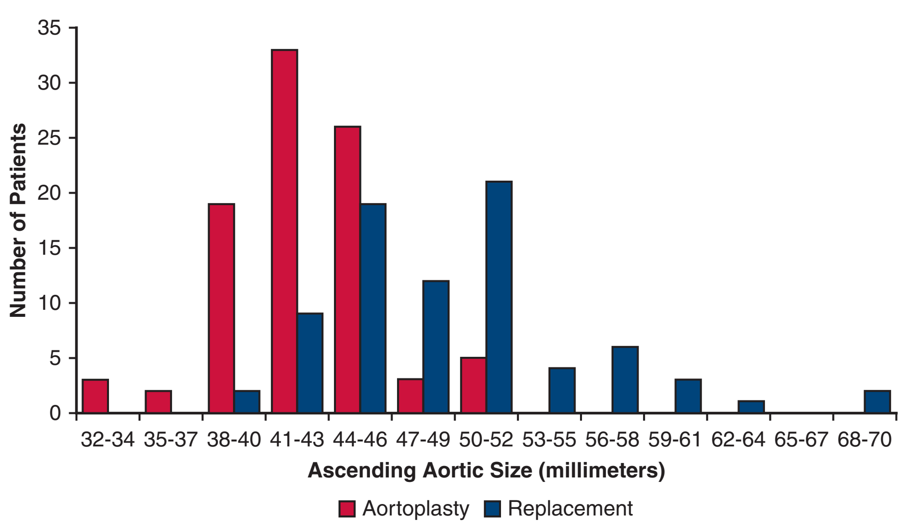


FIGURE E4. Association of ascending aortic size with aortic treatment. Larger degrees of aortic dilatation were most often treated with replacement; lesser degrees, with aortoplasty. However, long, thin aortas were replaced at small sizes and large areas of dilatation limited in length and located below the clamp were often treated with aortoplasty, including wedge resection of the greater curvature. Replacement was also increasingly used as experience increased. See Figure 1.

TABLE E1. Simple and complex Ross mortality and morbidity by tercile of time

Complication*	Simple (N = 419), n (%)			Complex (N = 283), n (%)			Total
	1987-1997 (N = 113)	1998-2008 (N = 176)	2009-2019 (N = 130)	1987-1997 (N = 59)	1998-2008 (N = 105)	2009-2019 (N = 119)	(N = 702), n (%)
Mortality	1	1	1	4	0	0	7 (1.0)
Morbidity							
Reoperation for bleeding	3	1	0	1	0	1	6 (0.9)
Other reoperation	0	1	0	0	0	1	2 (0.3)
Mechanical support†	0	1	0	0	1	3	5 (0.7)
Rescue CABG	0	0	2	0	0	1	3 (0.4)
Stroke‡	0	0	1	0	2	2	5 (0.7)
Right ventricular dysfunction§	0	1	2	1	1	0	5 (0.7)
Renal failure‖	0	0	1	2	1	2	6 (0.9)
Myocardial infarction	1	0	0	0	0	0	1 (0.1)
Respiratory failure¶	0	2	1	2	1	0	6 (0.9)
Permanent pacemaker	1	1	0	1	2	0	5 (0.7)
Deep sternal infection	1	0	0	0	1	0	2 (0.3)
Total patients with morbidity	6 (5.3)	7 (4.0)	7 (5.4)	7 (11.9)	9 (8.6)	10 (8.4)	46 (6.6)
Total with either morbidity or mortality	7 (6.2)	8 (4.5)	8 (6.2)	11 (18.6)	9 (8.6)	10 (8.4)	53 (7.5)

CABG, Coronary artery bypass grafting. *Complications are listed in decreasing order of author-designed priority. Patients with multiple complications are listed only once (under the highest-priority category). †Mechanical support: extracorporeal membrane oxygenation (n = 1), right ventricular assist device (n = 2), and balloon pump (n = 2). ‡Stroke defined as new cerebral imaging defect and/or persistent neurologic defect beyond 48 h. §Right ventricular dysfunction requiring inotropic support beyond 48 h. ‖Renal failure: acute kidney injury requiring temporary dialysis. (One case was persistent.) ¶Respiratory failure: ventilator support for >24 h (One patient needed temporary tracheostomy.)