SURGERY FOR CONGENITAL HEART DISEASE

FORTY-ONE YEARS OF SURGICAL EXPERIENCE WITH CONGENITAL SUPRAVALVULAR AORTIC STENOSIS

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Objective: **Several techniques for symmetric reconstruction of the aortic root in congenital supravalvular aortic stenosis have been developed, but it remains unclear whether these prove superior to patch enlargement of the noncoronary sinus alone. We reviewed our experience with surgical treatment of supravalvular aortic stenosis and investigated the impact of the surgical technique on long-term results.** ***Methods and results:*** **Seventy-five patients underwent operations to treat congenital supravalvular aortic stenosis at our institution between 1957 and 1998. Surgical procedures included patch enlargement of the noncoronary sinus only (n = 34), inverted bifurcated patch plasty (n = 35), and 3-sinus reconstruction of the aortic root (n = 6). There were 7 early deaths. Among those who survived the operation, 100% were alive at 5 years, 96% were alive at 10 years, and 77% were alive at 20 years. According to time-related analysis diffuse stenosis of the ascending aorta proved a risk factor for both survival and reoperation (*P* < .01 for each). Patients with multiple-sinus reconstructions of the aortic root accounted for only 2 of the 14 reoperations and none of the late deaths (both *P* < .001). Residual gradients were lower after multiple-sinus reconstruction of the aortic root (median 10 mm Hg vs 20 mm Hg for patch enlargement of the noncoronary sinus only, *P* = .008), as was the prevalence of moderate aortic regurgitation at follow-up (3% vs 22%, *P* = .05).** ***Conclusions:*** **Results of operations for supravalvular aortic stenosis improved greatly after the introduction of more symmetric reconstructions of the aortic root. Multiple-sinus reconstructions (inverted bifurcated patch plasty and 3-sinus reconstruction) resulted in superior hemodynamics and were associated with reductions in both mortality rate and need for reoperation. (J Thorac Cardiovasc Surg 1999;118:874-85)**

Congenital supravalvular aortic stenosis (SVAS) is the rarest obstructive lesion of the left ventricular outflow tract. SVAS represents an important feature of Williams syndrome but is also found in a familial form or as sporadic cases. The underlying cause is now known to be a spontaneous or inherited mutation of the elastin gene on chromosome 7.[1] The defining feature of the malformation is an aortic narrowing at the level of the sinotubular junction, but in some cases there is narrowing of the entire ascending aorta and arch branches. SVAS may also occur as part of a generalized arteriopathy involving both the systemic and pulmonary arte-

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rial systems. The geometry of the more proximal structures of the aortic root, although not primarily involved in the stenotic process, may also be distorted, potentially resulting in secondary pathologic changes. In addition to the effects of left ventricular pressure overload, patients are at risk for myocardial ischemia as a result of coronary ostial stenoses, decreased blood flow into the coronary sinuses, or hypertension-related coronary arteriosclerosis.

Since the first successful repair in 1956,[2] various surgical techniques for relief of SVAS have been developed. The extended aortoplasty aimed at a more symmetric augmentation of the aortic root by inserting an inverted bifurcated patch into the noncoronary sinus and the right coronary sinus.[3] More recently, several techniques to augment all 3 sinuses of Valsalva have been reported.[4-8] However, the originally described simple patch enlargement of the noncoronary sinus remains the preferred technique in some centers. The proponents of the inverted bifurcated patch plasty have hypothesized that the long-term results after a symmetric anatomic restoration of the aortic root are better, but because of the rarity of the disease limited data are available.[9-16] Among the surgical series published, few allow direct comparison between the results of single-patch enlargement and inverted bifurcated patch plasty. Reports of complex anatomic reconstructions are mostly anecdotal. We reviewed the Children's Hospital Boston experience with various techniques for correction of SVAS and investigated the impact of the surgical approach on long-term results.

Methods

To find the cases of patients who underwent operations for congenital SVAS at Children's Hospital Boston, the cardiology and cardiac surgical databases were reviewed, as was the database of the local multidisciplinary Williams syndrome clinic. Patients with acquired postsurgical SVAS were excluded, as were patients with multilevel left ventricular outflow tract obstruction including a hypoplastic but otherwise normal ascending aorta. The patient charts were reviewed and standardized questionnaires were sent to physicians and cardiologists caring for these patients. Patients or their parents were also contacted and sent a questionnaire in cases when no detailed recent follow-up information was available. The protocol was approved by the Children's Hospital institutional review board. Complete follow-up was obtained for 66 patients (88%) and partial information was obtained for the remaining 9 patients (12%). To classify the morphologic character of the lesion, the term *discrete* was used to describe the typical hourglass-shaped aortic narrowing at the level of the sinotubular junction, whereas a tubular narrowing involving the ascending aorta or beyond was termed *diffuse*.

Statistical analysis. The proportions of patients who died and who required reoperation were compared between the diamond-shaped patch and extended augmentation groups by the Fisher exact test. Stepwise multivariable logistic regression analysis was performed to identify the risk factors independently predictive of death and the need for reoperation, with the likelihood ratio χ^2 test used to assess significance.[17] The Hosmer-Lemeshow goodness-of-fit test was used to check the fit of the final models. Odds ratios and 70% confidence intervals (CIs) were calculated after adjustment for the following covariates: sex, type of stenosis, type of operation, year of operation, reoperation, presence of Williams syndrome, presence of aortic valve disease, and presence of pulmonary arterial stenosis. Aortic valve disease was defined as valvular stenosis (pullback gradient >20 mm Hg on catheterization), significant regurgitation, bicuspid aortic valve, markedly thickened leaflets, or adhesion of 1 or more leaflets to the supravalvular ridge. Estimated rates of survival and freedom from reoperation with 70% CIs were determined by the Kaplan-Meier product-limit method and survival curves were compared with the log-rank test.[18] The Cox proportional hazards regression model[19] was used to establish the variables independently associated with each outcome with risk measured by the hazard ratio. For survival analysis, reoperation was tested as a time-dependent covariate in the Cox model. A forward stepwise selection procedure was used to build the final multivariable models with the previously stated covariates. Preoperative, immediately postoperative, and follow-up pressure gradients were evaluated between the surgical groups by means of the Mann-Whitney *U* test. The analysis of the data was performed with the SPSS software package (version 8.0; SPSS Inc, Chicago, Ill).

Table I. *Associated anomalies of the ventricular outflow tracts and coronary arteries*

Anomaly	*No.*	*%*
Thickened aortic valve leaflets	19	25
Valvular aortic stenosis	13	17
Coarctation of the aorta	8	11
Biscuspid aortic valve	7	9
Sinus of Valsalva dilatation	7	9
Total with associated left ventricular outflow tract disease	31	41
Coronary artery dilation	12	16
Sinus of Valsalva inflow obstruction	5	7
Coronary artery stenosis	3	1
Coronary ostial stenosis	1	1
Total with associated coronary arterial disease	21	28
Branch pulmonary arterial stenosis	31	41
Pulmonary valve stenosis	10	13
Total with associated right-sided obstruction	32	43

Patient population. Between 1957 and 1998 a total of 75 patients underwent operations for congenital SVAS at Children's Hospital of Boston. Thirty-nine (52%) of the patients were male and 36 (48%) were female. The age at the

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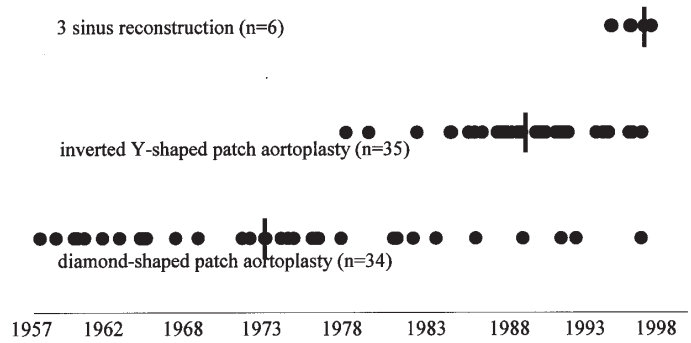

Fig 1. Date of operation grouped according to surgical technique for augmentation of aortic root in SVAS. *Vertical bars* indicate median date of operation for each technique. *Diamond-shaped patch aortoplasty* represents patch augmentation of noncoronary sinus only (Fig 2, **A**), *inverted Y-shaped patch aortoplasty* represents augmentation of noncoronary and right coronary sinuses (extended aortoplasty, Fig 2, **B**), and *3-sinus reconstruction* represents augmentation of all 3 sinuses (Brom technique[4] and modifications,[5] Fig 2, **C** and **D**).

time of operation ranged between 4 months and 27 years (median 7.4 years). In 46 cases (61%) a diagnosis of Williams syndrome was made by a medical geneticist. More recently the clinical diagnosis was supported by fluorescence in situ hybridization analysis of a deletion on chromosome 7q11.23. In 5 cases (7%) a familial history of SVAS, generalized arteriopathy, or both was known, and the remaining 24 cases (32%) were classified as sporadic. None of the patients with familial SVAS were developmentally delayed, whereas 1 of the patients with sporadic SVAS was.

The supravalvular narrowing was discrete in 56 cases (75%) and diffuse in 19 cases (25%). Branch pulmonary arterial stenoses (narrowing in diameter >50% as measured by angiography) were present in a total of 31 patients (41%). Prevalence of branch pulmonary arterial stenoses was 43% (20/46) among patients with Williams syndrome, 100% (5/5) among patients with familial SVAS, and 21% (5/24) among patients with sporadic SVAS. Associated anomalies of the left ventricular outflow tract or coronary arteries were present in 39 (52%) of the cases (Table I). Other cardiovascular anomalies were rare and included patent ductus arteriosus (n = 1), atrial septal defect (n = 1), tiny muscular ventricular septal defects (n = 2), and mitral valve prolapse (n = 1). Systemic arterial stenoses were demonstrated in 16 patients (21%) and involved the renal arteries (n = 7), aortic arch vessels (n = 8), and mesenteric vessels (n = 2).

Fifteen patients had previously undergone cardiovascular procedures. Seven patients had undergone procedures for aortic coarctation and 4 had undergone an aortic valvotomy. In 2 cases a transventricular pulmonary valvotomy with the Brock technique had been performed, and in 1 case division of a patent ductus arteriosus had been performed. In 2 cases a repair of SVAS had been attempted at another institution; both patients had persistent significant pressure gradients with symptoms. One patient underwent percutaneous angioplasty of a stenotic left carotid and innominate artery before the aortic procedure in an attempt to ensure cerebral perfusion during cardiopulmonary bypass.

Preoperative status. Thirty-one patients were in New York Heart Association functional class II, 2 were in class III, and 1 was in class IV and receiving inotropic support after an attempted aortic balloon valvuloplasty. Two patients receiving cardiopulmonary resuscitation underwent an emergency operation after cardiac arrest, 1 during cardiac catheterization and 1 during induction of anesthesia. Five patients (7%) had a history of 1 or more episodes of syncope, 7 (9%) had intermittent angina, and 29 patients (39%) were free of symptoms. In the symptom-free group the indication for surgery was a pressure gradient of more than 60 mm Hg with progression over time. A harsh systolic murmur was present in all cases and represented the most common cause for initial presentation. Preoperative left ventricle to aorta peak-to-peak pressure gradients were measured by cardiac catheterization (n = 59) or pulsed Doppler echocardiography (n = 23) and ranged between 35 and 191 mm Hg with a mean of 86 ± 29 mm Hg and a median of 88 mm Hg. Moderate aortic regurgitation was described in 7 cases (9%) and mild regurgitation was seen in 5 cases (7%). Electrocardiographic or echocardiographic evidence of moderate left ventricular hypertrophy was present in 41 cases (55%); severe hypertrophy with strain was present in 20 cases (27%).

Operative technique. Various operative procedures were performed; their temporal distribution mirrors the development of cardiac surgical techniques during the past 4 decades (Fig 1). Cardiopulmonary bypass was used in all cases after cannulation of the ascending aorta (in earlier years with a tube graft connected end to side to the aorta), the subclavian or innominate artery, or the femoral artery. Cardiac arrest was most frequently induced with cold crystalloid cardioplegia and in some cases with cold blood cardioplegia. The earlier operations were performed with ventricular fibrillation, with topical cooling alone, or after injection of potassium citrate into the coronary circulation. Deep hypothermic circulatory arrest was employed when the reconstruction extended into the aortic arch or when aortic arch vessels were involved.

A diamond-shaped patch was inserted in the ascending

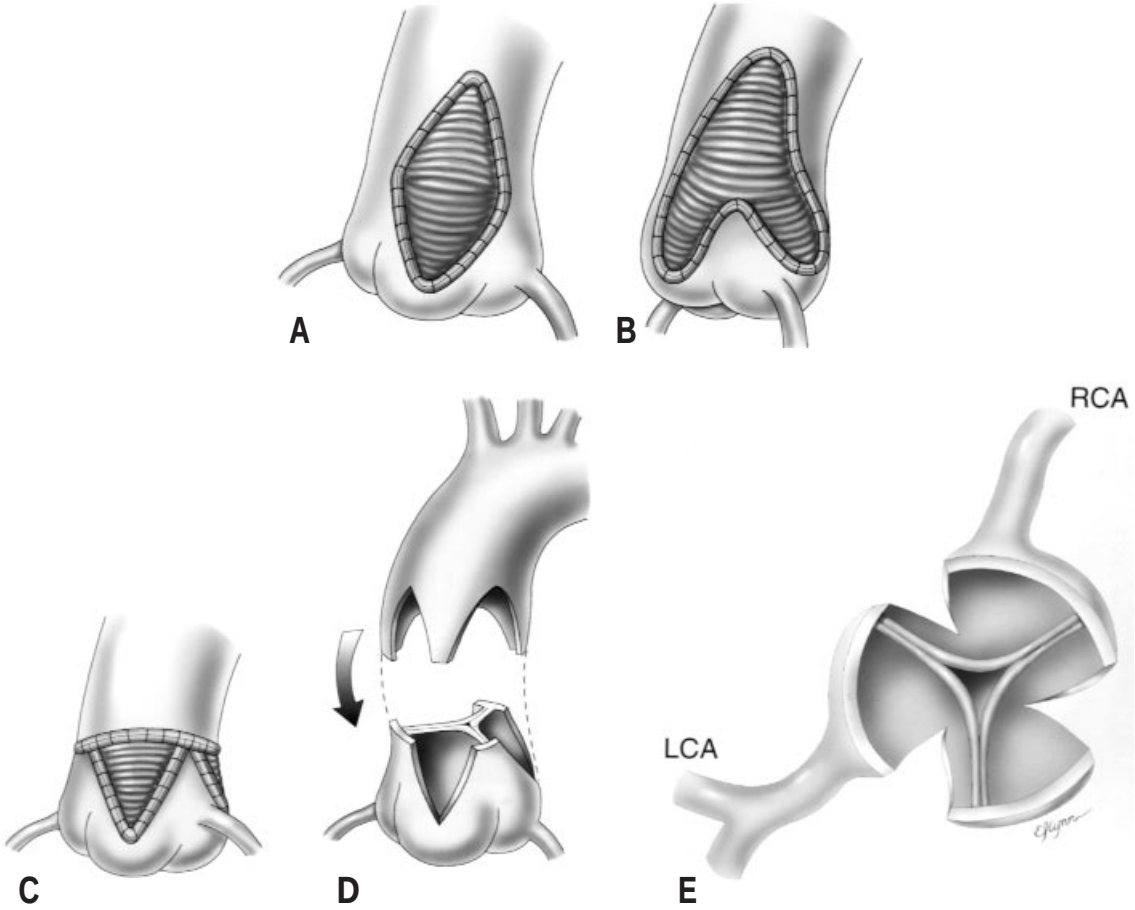

Fig 2. Surgical techniques used in our series for relief of supravalvular aortic stenosis. **A,** Diamond-shaped or teardrop-shaped patch extending in noncoronary sinus. **B,** Insertion of inverted bifurcated patch extending in noncoronary and right coronary sinuses (extended aortoplasty). **C,** Transection of aorta, incisions and patch insertions in all 3 sinuses, and reanastomosis (Brom technique[4]). **D,** Transection of aorta, incisions in all 3 sinuses, corresponding tailoring of distal aorta, and reanastomosis. **E,** Positions of 3 sinus incisions relative to coronary arteries. *RCA,* Right coronary artery; *LCA,* left coronary artery.

aorta after longitudinal incision through the stenotic region extending into the noncoronary sinus in 34 cases (Fig 2, *A*). Extensive resection of the stenotic ridge was frequently attempted but proved impossible in most cases because the ridge usually represented a constriction of the thickened aortic wall at the level of the leaflet hinge point, rather than a circumscribed fibrous structure.

An inverted bifurcated patch plasty (extended aortoplasty), as described by Doty and coworkers,[3] was used in 35 cases. An inverted Y-shaped incision was made into the ascending aorta down into the noncoronary sinus and the right coronary sinus to the left of the right coronary ostium (Fig 2, *B*). In 1 case the incision in the right coronary sinus had to be placed to the right of the right coronary ostium because the coronary artery was located too close to the commissure between left and right aortic leaflets.

More recently, techniques that enlarge the aortic root above all 3 sinuses of Valsalva have been employed. In 2 cases the technique ascribed to Brom[4] was used. The aorta was transected immediately above the level of the commissures. A longitudinal incision was then carried out into each of the 3 sinuses (left of the right coronary artery, right of the left coronary artery, and central in the noncoronary sinus, approximately halfway down into the respective sinuses of Valsalva) and 3 separate patches were inserted accordingly (Fig 2, *C*). The proximal aortic root thus enlarged was then reanastomosed to the distal aorta. In 4 cases a modification of this technique described by Myers and colleagues,[5] which also consists of transection of the aorta and opening of all 3 sinuses of Valsalva, was used. Here the distal aortic end was incised to create 3 corresponding flaps that were inserted into the sinus incisions when the aorta was reanastomosed (Fig 2, *D*).

To compare the results from inserting a diamond-shaped patch into the noncoronary sinus alone with a more symmetric augmentation of the aortic root, Doty and coworkers' extended aortoplasty[3] and the Brom technique[4] and its modi-

Table II. *Reoperations after surgical procedures for SVAS*

Type of operation	*Indication*	*Reoperation performed*	*Time after initial operation (y)*
Discrete stenosis			
Diamond	Valvular AS	AVR	24.2
Diamond	Mitral incompetence	Mitral valve replacement	23.8
Diamond	Valvular AS	AVR	23.1
Diamond, valvotomy	Valvular AS, recurrent SVAS	AVR, replacement of ascending aorta	19.1
Diamond	Valvular AS	AVR	14.4
Diamond, valvotomy	Valvular AS , SVAS	AVR, subvalvular myectomy	12.9
Diamond, AVR	Thrombosis of mechanical AVR	Reoperative AVR, replacement of ascending aorta	5.9
Diamond	Recurrent SVAS, aortic incompetence	AVR, extended aortoplasty (Y patch)	5.6
Diffuse stenosis			
Diamond	I: Valvular AS, recurrent SVAS	AVR, patch aortoplasty	18.2
	II: Mitral incompetence	Mitral valve replacement	19.2
Diamond	I: Recurrent SVAS, aortic incompetence	AVR, replacement of ascending aorta	10.3
	II: Persisting distal gradient	Left ventricular apex to descending aortic conduit	
Diamond, valvotomy	Restenosis	Left ventricular apex to descending aortic conduit	9.7
Diamond	Distal gradient	Left ventricular apex to descending aortic conduit	8.5
Y	Coarctation	Patch enlargement	5.4
Y	Distal recurrent SVAS	Tube graft ascending to descending aorta with branches to left carotid and innominate arteries	0.7

Diamond, Diamond-shaped patch aortoplasty; *AS*, aortic stenosis; *AVR*, aortic valve replacement; *Y*, inverted bifurcated patch plasty (extended aortoplasty).

fications[5] were combined into 1 group and termed *multiple-sinus reconstruction.*

Of the 56 patients with discrete SVAS, 24 had a single, diamond-shaped patch placed, 26 had an inverted bifurcated patch placed, and 6 underwent 3-sinus reconstruction. The patch material included preclotted or collagen-impregnated polyethylene terephthalate (Dacron, n = 29), autologous pericardium (n = 15), polytetrafluoroethylene (Gore-Tex,* n = 3, and Teflon, n = 1), and aortic homograft tissue (n = 4). Some tissue could be excised off the supravalvular ridge in 9 cases, and a digital or sharp valvulotomy of stenotic aortic valve leaflets was performed in 5 cases. A tethered aortic valve leaflet was mobilized in 3 cases. Aortic valve replacement at the initial operation was necessary for 2 patients with severely thickened and distorted aortic valve leaflets, resulting in valvular stenosis precluding reconstructive surgery. The Brom technique was used once in the fashion originally described by Brom[4] and once in a modified form with longitudinal incisions in the distal aorta directly opposite the proximal incisions with insertion of 3 elliptic pericardial patches to enlarge the circumferences of both proximal and distal aortic stumps. When the modification of the Brom technique described by Myers and associates[5] was used, both aortic ends could not always be completely reapproximated. After mobilization of the ascending aorta and circumferential resection of the stenotic part, a pericardial patch therefore had to be inserted anteriorly in 2 of the patients.

The 19 patients with diffuse narrowing of the ascending aorta were initially treated with a diamond-shaped (n = 9) or inverted bifurcated patch (n = 10) extending to the origin of the innominate artery. In 5 cases the incision in the anterior surface of the ascending aorta was further extended to the left across the undersurface of the aortic arch beyond the origin of the left carotid artery or distal to the left subclavian artery when a coarctation was suspected. Patch materials used were autologous pericardium and Dacron, sometimes in combination. Right coronary ostial stenosis was relieved in 1 case by direct excision; in a 4-year-old girl with long-segment stenosis of the left main coronary artery an internal thoracic artery bypass was employed. Concomitant procedures for right ventricular outflow tract obstruction or peripheral pulmonary artery stenosis were performed in 17 patients.

*Gore-Tex is a registered trademark of W. L. Gore & Associates, Inc, Flagstaff, Ariz.

Results

Early results. There were 7 early deaths (9% early mortality rate). Early in the series (1957, 1960, and 1968), when mechanical circulatory support was not available, 3 patients died during the operation. Two later patients (1984 and 1985) who underwent emergency procedures for preoperative cardiac arrest could not be successfully weaned from bypass and died. Both patients had severe generalized arteriopathy, 1 the familial form and 1 Williams syndrome. Two later (1995 and 1996) patients with severe generalized arterial disease as part of Williams syndrome had low cardiac output develop after the operation and received extracorporeal membrane oxygenation for 4 days. Neither of these patients could be weaned from extracorporeal membrane oxygenation. Postoperative mor-

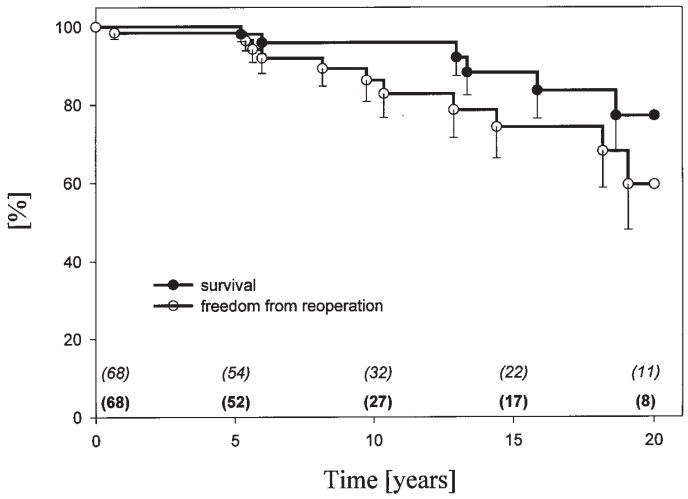

Fig 3. Kaplan-Meier 20-year estimates of freedom from reoperation and survival, excluding operative deaths. *Error bars* indicate lower half of 70% CI. Numbers of patients at risk are in *italics* (survival) and *bold* (freedom from reoperation).

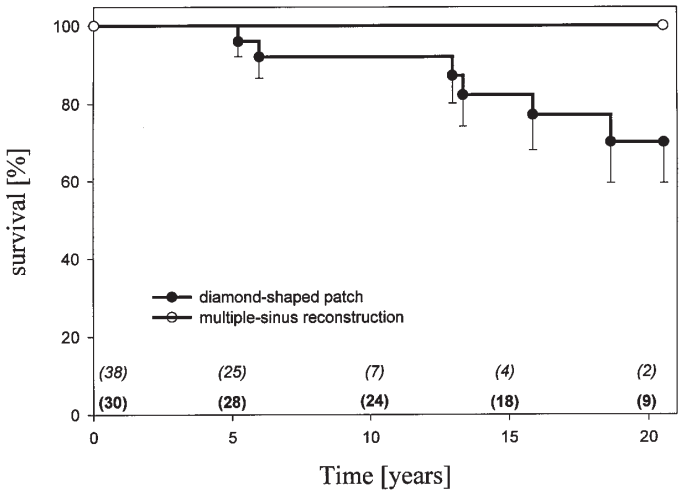

Fig 4. Kaplan-Meier 20-year estimates of survival according to type of operation, excluding operative deaths (*P* = .13, log-rank test). *Error bars* indicate lower half of 70% CI. Numbers of patients at risk are in *italics* (multiple-sinus reconstruction) and *bold* (diamond-shaped patch). *Diamond-shaped patch* represents patch augmentation of noncoronary sinus only (Fig 2, **A**); *multiple-sinus reconstruction* represents inverted bifurcated patch plasty and Brom technique[4] and modifications.[5]

bidity included bleeding (n = 3) and pericardial effusion (n = 5), and systemic hypertension necessitating intravenous antihypertensive medication was a frequent occurrence (n = 18).

Survival. Follow-up included the 68 patients surviving the initial operation. It ranged between 6 months and 37.4 years (mean 12.8 years). Seven late deaths occurred between 5 and 28 years after the operation. Four late deaths of unknown cause were classified as sudden deaths and may have been related to ventricular arrhythmia. The first of these patients died in 1980, 16 years after diamond-shaped patch enlargement and aortic valvotomy, again followed by implantation of a left ventricle to descending aorta conduit. The second patient died in 1980, 13 years after diamond-shaped patch enlargement and aortic valvotomy. He had subse-

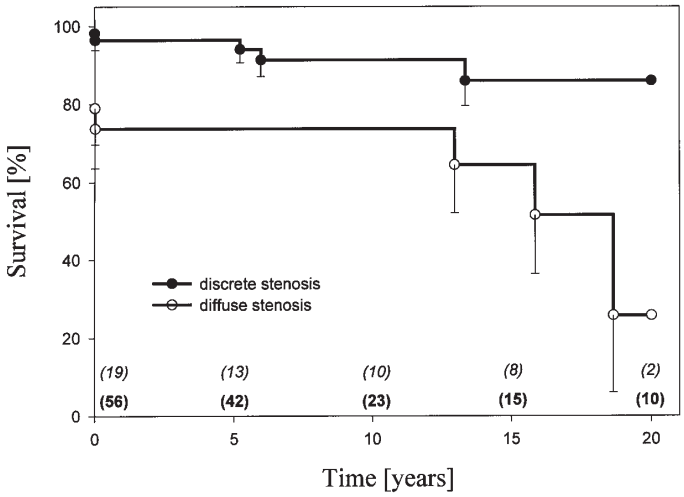

Fig 5. Kaplan-Meier 20-year estimates of survival according to type of stenosis (P = .002, log-rank test). *Error bars* indicate lower half of 70% CI. Numbers of patients at risk are in *italics* (diffuse stenosis) and *bold* (discrete stenosis).

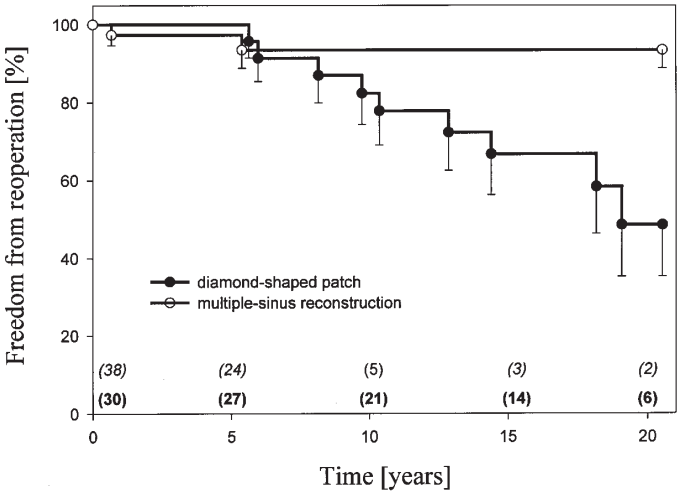

Fig 6. Kaplan-Meier 20-year estimates of freedom from reoperation according to type of operation (P = .43, log-rank test). *Error bars* indicate lower half of 70% CI. Numbers of patients at risk are in *italics* (multiple-sinus reconstruction) and *bold* (diamond-shaped patch). *Diamond-shaped patch* represents patch augmentation of noncoronary sinus only (Fig 2, **A**); *multiple-sinus reconstruction* represents inverted bifurcated patch plasty and Brom technique[4] and modifications.[5]

quently undergone aortic valve replacement for aortic valve stenosis. The third patient died in 1987, 13 years after the initial patch enlargement of the ascending aorta. She subsequently underwent replacement of aortic valve and ascending aorta, followed by insertion of a left ventricle to descending aorta conduit (Table II). The fourth patient died in 1992, 28 years after diamond-shaped patch enlargement. The last follow-up examination in 1991 revealed a residual gradient of 64 mm Hg and ventricular extrasystoles. One additional patient died (1981) in left ventricular failure 5 years after diamond-shaped patch enlargement of discrete SVAS with mobilization of a tethered left coronary leaflet. This patient had a persistent gradient of 20 mm Hg and moderate aortic regurgitation, as determined by catheterization 4 years after the operation. Another

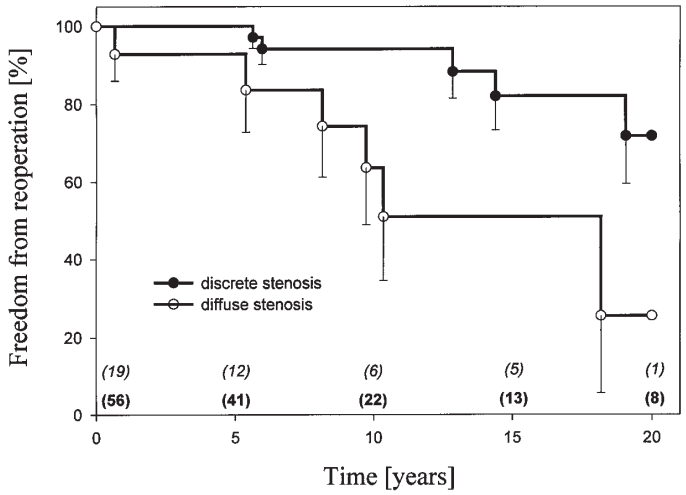

Fig 7. Kaplan-Meier 20-year estimates of freedom from reoperation according to type of stenosis (P = .002, log-rank test). *Error bars* indicate lower half of 70% CI. Numbers of patients at risk are in *italics* (diffuse stenosis) and *bold* (discrete stenosis).

patient underwent aortic valve and ascending aorta replacement for recurrent SVAS 18 years after the initial operation. She remained in congestive heart failure and underwent mitral valve replacement for progressive mitral regurgitation. Ventricular function continued to deteriorate, however, and she died 6 months later (1983) in multiorgan failure. One patient was admitted 6 years after aortic valve replacement and patch enlargement of the aorta with a thrombosed mechanical prosthesis. He died (1980) after attempted reoperation. Kaplan-Meier estimates of survival, including operative deaths, were 91% at 5 years, 87% at 10 years, and 70% at 20 years. Survival rates excluding operative deaths are depicted in Fig 3.

Risk factor analysis. Comparing the surgical techniques, 11 patients (32%) in the diamond-shaped patch group and 3 (7%) in the multiple-sinus reconstruction group died (P = .007, Fisher exact test). Stepwise multivariable logistic regression indicated that type of operation and type of stenosis were independent risk factors for death. The Hosmer-Lemeshow test indicated no significant departure from good model fit (P = .42). The odds of death were significantly higher for patients in the diamond-shaped patch group (adjusted odds ratio 6.5, 70% CI 3.2-13.1, P = .006). In addition, patients with diffuse stenosis had a significantly higher risk of death (adjusted odds ratio 6.5, 70% CI 3.4-12.5, P = .005). Excluding operative deaths, the multivariable analysis revealed that the type of operation was the only risk factor for death (P <.001). Sex, presence of Williams syndrome, presence of pulmonary arterial stenosis, presence of aortic valve disease, and year of operation were not identified as predictive of death (all P > .20).

Time-related analysis. Although no late deaths occurred when a multiple-sinus reconstruction was used (Fig 4), univariate time-related analysis by the Kaplan-Meier method of those who survived the operation revealed no significant differences according to the type of operation. Diffuse stenosis was associated with a faster rate of death (Fig 5). Sex, era of operation, presence of Williams syndrome, and presence of aortic valve disease did not influence time-related survival (all P > .20). Multivariable analysis with the Cox model confirmed that diffuse stenosis was the only variable independently predictive of decreased survival time (hazard ratio 5.0, 70% CI 3.0-8.2, P = .004). Survival time was not associated with sex, type or year of operation, presence of Williams syndrome, presence of pulmonary arterial stenosis, or presence of aortic valve disease. The final multivariable Cox regression model revealed that reoperation, treated as a time dependent covariate, had a significant impact on the monthly instantaneous risk of death (hazard ratio 5.8, 70% CI 2.2-15.7, P = .04).

Reoperation. Fourteen reoperations were performed during the follow-up period and are listed in Table II. Kaplan-Meier estimates of freedom from reoperation were 98% at 5 years, 86% at 10 years, and 66% at 20 years (Fig 3). In 3 patients with diffuse SVAS and recurrent gradients of more than 100 mm Hg, a left ventricular apex to aorta conduit was implanted. Two

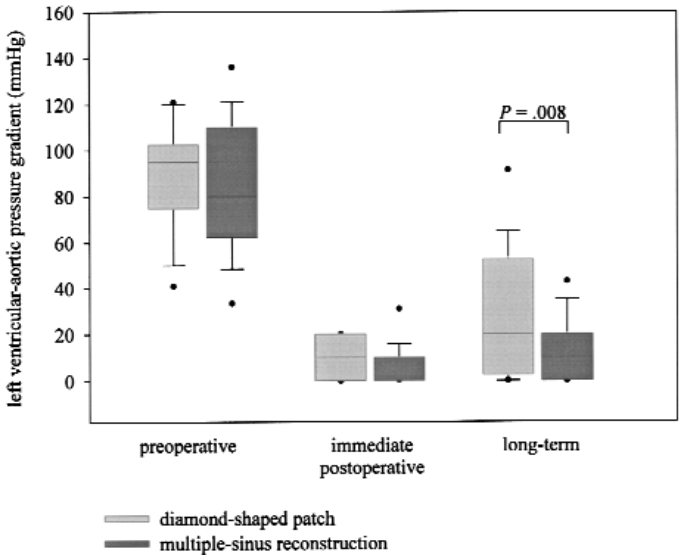

Fig 8. Peak pressure gradients according to type of operation (long-term gradients measured by echocardiography [n = 42] or cardiac catheterization [n = 20]). *Line* within box represents median; *box* represents 25th and 7th percentiles; *whiskers* represent 10th and 90th percentiles; *dots* represent 5th and 95th percentiles. *Diamond-shaped patch* represents patch augmentation of noncoronary sinus only (Fig 2, **A**); *multiple-sinus reconstruction* represents inverted bifurcated patch plasty and Brom technique[4] and modifications.[5]

of these patients died suddenly, one 1 year after implantation of the conduit and the other 8 years after implantation. There had been no evidence of conduit dysfunction; however, autopsies were not performed. The third patient is alive and free of symptoms. She has lived for 26 years with a 22-mm Carpentier-Edwards valved conduit (Baxter Healthcare Corporation CardioVascular Group, Irvine, Calif) without anticoagulation. Another patient, with Williams syndrome and generalized arteriopathy, underwent implantation of a Dacron conduit from ascending to descending aorta with a bifurcated branch graft going to the left carotid and innominate arteries. He also underwent multiple dilatations of supra-aortic vessels and coil occlusion of a collateral vessel between right internal thoracic artery and right pulmonary artery.

Risk factor analysis. Comparing the surgical techniques, 12 patients (35%) in the diamond-shaped patch group and 2 patients (5%) in the multiple-sinus reconstruction group required a reoperation ($P < .001$, Fisher exact test). Stepwise multivariable logistic regression, including only those patients who survived the operation, confirmed that type of operation was the only independent risk factor for reoperation, and the Hosmer-Lemeshow test indicated good model fit ($P = .63$). The odds of reoperation were higher for patients who underwent insertion of a diamond-shaped patch (adjusted odds ratio 12.0, 70% CI 5.7-25.4, $P < .001$). Sex, year of operation, type of stenosis, presence of Williams syndrome, presence of pulmonary arterial stenosis, and presence of aortic valve disease were not predictive of the need for reoperation in the univariate or multivariable analyses.

Time-related analysis. Comparison of the Kaplan-Meier freedom from reoperation curves revealed no significant difference according to the type of operation ($P = .43$, log-rank test). Nevertheless, it is notable that only 2 reoperations were performed after initial inverted bifurcated patch plasty (Fig 6) and that both were for stenosis at the distal end of the patch and were not related to the aortic valve (Table II). Further analysis confirmed that patients with diffuse stenosis required reoperation more frequently and sooner than did those with discrete stenosis (Fig 7). The only predictor of freedom from reoperation in multivariable analysis with the Cox regression model was the type of stenosis (hazard ratio 5.6, 70% CI 2.1-15.2, $P = .008$). Freedom from reoperation was not found to be related to sex, type or year of operation, presence of pulmonary arterial stenosis, or presence of aortic valve disease in the univariate or multivariable time-related analysis.

Hemodynamics. The average immediate postoperative gradient (measured during the operation [n = 17] or before discharge by echocardiography [n = 22]) was 8.2 ± 12.5 mm Hg, with a median of 0 mm Hg (range 0-40 mm Hg). Long-term gradients were available for

52 patients and were measured by echocardiography (n = 42), cardiac catheterization (n = 20), or both (n = 10). Average long-term gradient was 19.7 ± 23.1 mm Hg, with a median of 13 mm Hg (range 0-100 mm Hg). Patients who underwent multiple-sinus reconstruction of the aortic root had significantly lower gradients at follow-up than did patients who underwent insertion of a diamond-shaped patch (median 10 mm Hg vs 20 mm Hg, $P = .008$ (Fig 8). Patients with diffuse stenosis did not have significantly higher gradients at late follow-up than did those with discrete stenosis (median 15 mm Hg vs 13 mm Hg, $P = .77$). Mild aortic regurgitation was described in 20 patients and moderate aortic regurgitation was described in 5. There was a higher frequency of moderate aortic regurgitation among patients with a diamond-shaped patch than among those with multiple-sinus reconstruction (4/18, 22%, vs 1/31, 3%, $P = .05$). No association was detected between the type of stenosis and aortic regurgitation ($P = .46$).

Functional class. The functional class was assessed in 57 cases. At the time of most recent follow-up 41 patients (82%) were free of any cardiovascular symptoms. Five patients (9%) were in New York Heart Association functional class II, 2 (4%) reported chest pain on exertion, and 2 had had a syncopal episode of unknown cause. One patient with multiple disabilities and seizures reported both chest pain and syncope. In all but 2 patients with Williams syndrome the physician following the patient's case or the patient's parents deemed the mental development to be delayed for age. All but 1 of these patients had received special education and support. In addition, 1 patient with the sporadic form of SVAS was developmentally delayed and had attended special education classes. All patients with familial SVAS developed appropriately for age. Most parents reported that the patient's quality of life was good or very good.

Discussion

The morphologic spectrum of SVAS has been well defined during the last 4 decades.[19-23] The concept of an isolated supravalvular membrane has been abandoned, and it has become clear that in most if not all cases the supravalvular narrowing is part of a general disease of the arterial wall with a genetic origin. However, the reason that the stenosis is most prominent at the sinotubular junction remains subject to speculation. Because the sinotubular junction is at the level of the tops of the valvular commissures, the geometry of the entire aortic valve apparatus is disturbed.[24] However obvious this may seem, it was not until the early 1980s that this feature of SVAS was fully appreciated by both surgeons and morphologists. Before this period the main goal of surgery was relief of excessive left ventricular pressure overload by as simple and safe a means as possible. Insertion of a simple diamond-shaped patch in the noncoronary sinus was therefore used. Twenty-two years have passed since Keane and colleagues[10] reported on the first patients to undergo surgical procedures for SVAS at Children's Hospital Boston. Soon after that report Doty and coworkers[3] presented their technique of extended augmentation of the aortic root, and this technique was applied in our institution and became the method of choice.

Subsequently, on the basis of experience with valve-sparing replacement of the ascending aorta in adults and with the arterial switch and Ross procedures in younger patients, techniques were developed to more completely restore the geometry of the aortic root in SVAS. Brom[4] presented his technique, which involves insertion of patches in all 3 sinuses after transection of the aorta. Myers and associates[5] and Chard and Cartmill[6] sought to achieve the same result without any patches. Al-Halees[8] and colleagues interposed autologous pulmonary artery. Finally, Steinberg and colleagues[7] modified Doty and coworkers' original technique[3] by inserting an extra patch in the left coronary sinus in addition to the inverted Y-shaped patch in the right and noncoronary sinuses. This is of particular importance because the supravalvular ridge can be most prominent above the left coronary sinus and may impair coronary perfusion, especially when the leaflet becomes more rigid with age. A circular anastomosis of the aorta, as in the original Brom technique,[4] could potentially create a stenosis at the new sinotubular junction, although no such case has been reported as yet. Longitudinal incisions in the distal aorta followed by end-to-end anastomosis or patch insertion allow additional augmentation of the distal aortic end and may help to avoid this problem.

The time-related comparisons between the surgical groups of the Kaplan-Meier estimates for both survival and freedom from reoperation did not reach statistical significance. However, it is notable that there were no late deaths of patients with inverted bifurcated patches as opposed to the single patch technique. Furthermore, the group with extended augmentation accounted for only 2 of the reoperations, both of which were in patients with severe generalized arteriopathy and were not related to the aortic valve. Consistent with this observation, the risk factor analysis did identify multiple-sinus reconstruction of the aortic root as associated with reductions in mortality rate and the need for reoperation. Significantly lower long-term pressure gradients also add to the evidence in favor of a more extensive aortic reconstruction. When van Son and

associates[15] presented the Mayo Clinic experience with operations for SVAS, they concluded that the simple teardrop-shaped patch was usually sufficient to both reduce the gradient and preserve valve function. There were only 7 patients with inverted bifurcated patches in their series, however, and none of these had complete restoration of the stenosed sinotubular junction. Braunstein and coworkers[13] had previously come to the same conclusion on the basis of a total of 10 patients who underwent reconstruction of the aortic root. Our extensive experience should allow better comparison between both techniques and demonstrates the favorable results of an extended augmentation more clearly.

Another surgically challenging feature of SVAS is treatment of the diffuse form. Long-term survival of patients with the diffuse form was not significantly impaired with respect to that of patients with the discrete form, but the patients in this group did account for 6 of the 7 early deaths. In severe arteriopathy it is difficult to reduce the aortic gradient without moving the stenosis to the distal end of the patch. We have tried to account for this by inserting a pericardial patch along the entire ascending aorta and the undersurface of the aortic arch distal to the left subclavian artery whenever a significant degree of hypoplasia is suspected.

Pathologic changes of the coronary arteries and myocardial ischemia in SVAS have been described by several authors and, although rare, serve as another argument in favor of an early and complete anatomic reconstruction.[25] We saw 1 patient in whom an ostial stenosis of the right coronary artery could be directly resected and 1 in whom an internal thoracic artery bypass graft was inserted. Patch augmentation of ostial stenosis has been described by other groups and is a further option in some cases.[26-28] In addition to severe ventricular hypertrophy, the coronary circulation of patients with severe arteriopathy may be more sensitive to changes in blood pressure and viscosity during the perioperative period.

Some degree of aortic valve disease was found in a substantial number of patients, similar to other series, but this was not a statistically significant risk factor with respect to either death or reoperation. Among the 7 patients with a bicuspid aortic valve, 2 ultimately underwent valve replacement for valvular stenosis 12 and 15 years after patch enlargement. On the basis of these data we do not recommend initial replacement of a bicuspid valve in SVAS, as was recently suggested by Delius and colleagues.[29]

Limitations of the study. There are various limitations in comparing results of surgical techniques that have evolved through a long period, especially in a rapidly developing field such as cardiac surgery and when the number of patients is limited. As depicted in Fig 1, most of the patients who received a diamond-shaped patch were operated on before 1980. The first inverted Y-shaped patch aortoplasty at our institution was performed in 1978, and there is considerable overlap between the groups. When interpreting the presented data, however, it should be taken into account that most of the diamond-shaped patch reconstructions were performed in an era when the overall risk of surgery was higher and cardiac surgeons faced a multitude of problems other than surgical technique itself. We attempted to account for this by excluding operative deaths from the time-related survival analysis. Another contributing factor responsible for the lack of statistically significant difference between the 2 surgical groups in the time-related analyses may be the small number of patients with multiple-sinus reconstruction and a follow-up longer than 10 years. Furthermore, we recognize that a multiple-sinus reconstruction of the aortic root in SVAS poses technical difficulties not encountered with the insertion of a simple diamond-shaped patch. For example, we recall a case in which the right coronary artery appeared to be distorted after insertion of an inverted bifurcated patch.

Summary. Even though the time-related analysis did not provide conclusive evidence of the superiority of multiple-sinus reconstructions of the stenotic supravalvular aorta with respect to enlargement with a diamond-shaped patch, we did demonstrate that surgical treatment of SVAS by augmenting the aortic root in 2 or 3 sinuses of Valsalva is associated with a lower mortality rate and fewer reoperations. A symmetric and thus more anatomic restoration of the distorted aortic root in SVAS probably leads to a more physiologic flow pattern, preserving valve function better than does augmentation of the noncoronary sinus only. Insertion of at least an inverted bifurcated patch in the noncoronary and right coronary sinuses is technically not demanding and likely will lead to improvements in long-term survival and freedom from reoperation rates.

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