IMPORTANCE Bicuspid aortic valve (BAV) repair has been used in limited cohorts, but its long-term results in a large population are unknown.

OBJECTIVES To analyze the long-term stability of BAV repair for survival and the factors associated with repair failure and to evaluate whether a differentiated anatomic repair approach may improve repair stability.

DESIGN, SETTING, AND PARTICIPANTS In this case series, 1024 patients underwent BAV repair for aortic regurgitation or aneurysm between October 1995 and June 2018, with a mean (SD) follow-up time of 56 (49) months and maximum follow-up of 271 months. Systematic modifications in technique based on anatomic principles were introduced in 2009 and applied for the last 727 patients. Data were acquired prospectively and analyzed retrospectively.

EXPOSURES Repair of BAV with or without concomitant aortic replacement, as well as postoperative clinical and echocardiographic follow-up.

MAIN OUTCOMES AND MEASURES Survival and incidence of reoperation or recurrent aortic regurgitation, as well as factors associated with valve repair failure.

RESULTS Among the 1024 patients in the study (920 male [89.8%]; mean [SD] age, 47 [13] years [range, 15-86 years]), the survival rate at 15 years was 82.1%. The cumulative incidence of reoperation was 30.7% (95% CI, 22.7%-38.7%) at 15 years. Cusp calcification (subdistribution hazard ratio, 1.78; 95% CI, 1.14-2.77; P = .01), asymmetric commissural orientation (subdistribution hazard ratio, 1.95; 95% CI, 1.02-3.72; P = .04), and use of a pericardial patch for cusp repair (subdistribution hazard ratio, 5.25; 95% CI, 3.52-7.82; P < .001) were associated with time to reoperation. At 10 years, the incidence of reoperation was significantly reduced among patients who received the anatomic repair concept compared with those who had undergone surgery in the earlier period (8.8% vs 24.6%; P < .001).

CONCLUSIONS AND RELEVANCE This study suggests that survival after BAV repair is excellent and that a large proportion of BAV repairs will remain stable. Repair stability can be markedly improved by an anatomic repair concept. Cusp calcification and the need for cusp repair using a patch remain the factors most strongly associated with valve failure. In those instances, valve replacement should be preferred.
The bicuspid aortic valve (BAV) is the most frequent congenital cardiac anomaly.\textsuperscript{1} It is characterized by a variable degree of fusion between 2 cusps and the presence of a nonfused cusp that is almost always larger than the 2 components of the fused cusp (Figure 1A).\textsuperscript{2,3} There is further anatomic variability that is less frequently appreciated; there are different fusion patterns, and the degree of fusion varies (Figure 1A).\textsuperscript{2,3} In addition, there is variability of commissural orientation ranging from a symmetric configuration to one that is close to a tricuspid design (Figure 1A).\textsuperscript{2,3} A relevant proportion of individuals with BAV will need treatment for either aortic regurgitation (AR) or ascending aortic aneurysm.\textsuperscript{1,4}

Reconstruction of the regurgitant BAV was already proposed more than 25 years ago with good early results.\textsuperscript{5} Regurgitation was assumed to be solely due to prolapse of the fused cusp, which was corrected as the key intervention. With longer follow-up, results were sobering because a relevant proportion of repaired valves failed within the first 5 postoperative years.\textsuperscript{6} Initially, a specific repair type (ie, triangular resection) was assumed to predispose the repaired valve to failure.\textsuperscript{6}

Based on the analysis of failed BAVs, we realized that symmetric prolapse was an important mode of failure.\textsuperscript{7} This could be avoided using the effective height (eH) concept, measured as the height difference between the basal plane and free margins in diastole\textsuperscript{8} (Figure 1B). Normal data on tissue height allowed for improved selection of adequate valves for repair.\textsuperscript{9} The analysis of a larger patient cohort then identified important factors associated with valve failure (namely, annular size and circumferential orientation of the commissures of the nonfused cusp).\textsuperscript{10} Moreover, the use of autologous pericardium as partial cusp replacement was also associated with unacceptable rates of failure.\textsuperscript{10}

These results led us to modify our repair approach by selecting patients more carefully. More important, we developed a suture annuloplasty\textsuperscript{11} to address annular dilatation, with good midterm results.\textsuperscript{12} We also modified the circumferential orientation, attempting to come as close as possible to a symmetric configuration.\textsuperscript{13,14}

During the past 10 years, we have consistently applied this differentiated anatomic repair concept in repairing BAVs. With follow-up reaching 20 years, we now intend to analyze the long-term durability of BAV repair and to evaluate current results of the anatomic repair concept.

Methods

Between October 1995 and June 2018, 1024 patients with a BAV underwent valve-preserving surgery for AR (n = 745) and/or ascending aortic aneurysm (n = 249) in our institution. Patients’ ages ranged from 15 to 86 years (mean [SD] age, 47 [13] years; 920 male [89.8%]) (Table 1). Preoperative AR was relevant (III° or IV°) in most patients (784 [76.6%]). The left ventricular end-systolic diameter ranged from 22 to 71 mm (mean [SD], 43 [8] mm), the left ventricular end-diastolic diameter ranged from 38 to 86 mm (mean [SD], 61 [9] mm), the maximum sinus diameter was 71 mm (mean [SD], 42 [8] mm), and

Figure 1. Different Bicuspid Aortic Valve (BAV) Phenotypes and Landmarks of the Aortic Root

A, Different BAV phenotypes: symmetric (commissural orientation, 160°-180°), asymmetric (commissural orientation, 140°-155°), and very asymmetric (commissural orientation, <140°). The length of fusion varies between the phenotypes. It is longest in symmetric and shortest in asymmetric BAVs (modified according to de Kerchove et al\textsuperscript{2}). B, Landmarks of the aortic root: effective height (eH), aortic annulus (AN), sinotubular junction (STJ), and coaptation height (cH). Effective height is measured using a special caliper.
Table 1. Perioperative Patient Data

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patients, No. (%) (N = 1024)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male sex</td>
<td>920 (89.8)</td>
</tr>
<tr>
<td>Age, mean (SD), y</td>
<td>47 (13)</td>
</tr>
<tr>
<td>AR preoperatively</td>
<td></td>
</tr>
<tr>
<td>&lt;Grade III</td>
<td>240 (23.4)</td>
</tr>
<tr>
<td>≥Grade III</td>
<td>784 (76.6)</td>
</tr>
<tr>
<td>Fusion</td>
<td></td>
</tr>
<tr>
<td>Right-left</td>
<td>873 (85.3)</td>
</tr>
<tr>
<td>Right-nonfused</td>
<td>144 (14.1)</td>
</tr>
<tr>
<td>Left-nonfused</td>
<td>7 (0.7)</td>
</tr>
<tr>
<td>Primary indication</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>745 (72.8)</td>
</tr>
<tr>
<td>Aneurysm</td>
<td>249 (24.3)</td>
</tr>
<tr>
<td>Other</td>
<td>30 (2.9)</td>
</tr>
<tr>
<td>Preoperative LVESD, mean (SD), mm</td>
<td>43 (8)</td>
</tr>
<tr>
<td>Preoperative LVEDD, mean (SD), mm</td>
<td>61 (9)</td>
</tr>
<tr>
<td>Postoperative LVESD, mean (SD), mm</td>
<td>41 (7)</td>
</tr>
<tr>
<td>Postoperative LVEDD, mean (SD), mm</td>
<td>54 (7)</td>
</tr>
<tr>
<td>Preoperative sinus, mean (SD), mm</td>
<td>42 (8)</td>
</tr>
<tr>
<td>Preoperative basal ring, mean (SD), mm</td>
<td>30 (4)</td>
</tr>
<tr>
<td>Standard repair</td>
<td>917 (89.6)</td>
</tr>
<tr>
<td>Fused cusp</td>
<td></td>
</tr>
<tr>
<td>Central plication</td>
<td>593/917 (64.7)</td>
</tr>
<tr>
<td>Triangular resection</td>
<td>210/917 (22.9)</td>
</tr>
<tr>
<td>Nonfused cusp intervention</td>
<td>546/917 (59.5)</td>
</tr>
<tr>
<td>Tricuspid-like repair</td>
<td>107 (10.4)</td>
</tr>
<tr>
<td>Pericardial patch</td>
<td>138 (13.5)</td>
</tr>
<tr>
<td>Suture annuloplasty</td>
<td>591 (57.7)</td>
</tr>
<tr>
<td>Subcommisural plication</td>
<td>107 (10.4)</td>
</tr>
<tr>
<td>Concomitant procedures</td>
<td>244 (23.8)</td>
</tr>
<tr>
<td>Partial arch replacement</td>
<td>122 (11.9)</td>
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<tr>
<td>Total arch replacement</td>
<td>4 (0.4)</td>
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<tr>
<td>Elephant trunk</td>
<td>2 (0.2)</td>
</tr>
<tr>
<td>MVR</td>
<td>32 (3.1)</td>
</tr>
<tr>
<td>TVR</td>
<td>12 (1.2)</td>
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<tr>
<td>Ablation</td>
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<tr>
<td>CABG</td>
<td>50 (4.9)</td>
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<tr>
<td>Closure</td>
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<tr>
<td>PFO</td>
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<tr>
<td>VSD</td>
<td>2 (0.2)</td>
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<tr>
<td>Septal myectomy</td>
<td>6 (0.6)</td>
</tr>
<tr>
<td>PTE</td>
<td>1 (0.1)</td>
</tr>
<tr>
<td>PDA</td>
<td>1 (0.1)</td>
</tr>
</tbody>
</table>

Abbreviations: AR, aortic regurgitation; ASD, atrial septal defect; CABG, coronary artery bypass grafting; LVESD, left ventricular end-systolic diameter; LVEDD, left ventricular end-diastolic diameter; MVR, mitral valve repair; PDA, patent ductus arteriosus; PFO, patent foramen ovale; PTE, pulmonary thromboendarterectomy; TVR, tricuspid valve repair; VSD, ventricular septal defect.

a basal diameter of 28 mm or more was present in 795 patients (77.6%). The investigation was approved by the Saarland University Regional Ethics Committee for the analysis and publication of patient data in anonymized fashion. All patients provided written and oral consent.

Cusp fusion was mostly seen between the right and the left coronary cusp (873 [85.3%]) (Table 1), with varying extent of fusion from minimal (3-4 mm) to complete (771 [75.3%]). The commissural orientation of the nonfused cusp varied (Figure 1A), with predominant orientation of 160° or more (712 [69.5%]). An asymmetric orientation (140°-155°) was present in 205 patients (20.0%) and a very asymmetric orientation (<140°) was observed in 107 individuals (10.4%). Cusp calcification was present in 182 individuals (17.8%). Cardiac comorbidities requiring additional surgical treatment were present in 244 individuals (23.8%).

Technique

Aortic valve repair (AVr) was performed in the presence of preserved aortic root dimensions (sinus diameter, <42-45 mm; 618 individuals [60.4%]). Of those individuals, 180 (29.1%) required concomitant tubular aortic replacement. In the presence of root dilatation (sinus diameter, >42-45 mm), root remodeling (RR) was performed (406 [39.6%]).

Aortic valve function and root dimensions were assessed intraoperatively by transesophageal echocardiography (HDI 3000; Advanced Technology Laboratories or Vivid e9 or S70; General Electric). The chest was opened via a median sternotomy followed by aortic and right atrial cannulation. The aorta was transected transversely above the sinotubular junction, and blood cardioplegia was given directly into the coronary ostia. Standard BAV repair consisted of plication of the 2 components of the fused cusp, which was performed for all symmetric and asymmetric BAVs (917 [89.6%]). In the presence of limited fusion and very asymmetric commissural orientation (<140°), the repair was performed according to the principles of tricuspid AVr (107 [10.4%]).

Initially, cusp prolapse was visually assessed by comparison of the cusp margins. Starting in 2004, valve assessment included measurement of both geometric height9 and eH8 in 205 patients (20.0%) and a very asymmetric orientation (<140°) in 107 individuals (10.4%).

The different surgical techniques remained principally constant over time and have been described previously.16 If concomitant tubular aortic replacement was necessary in addition to AVr, the graft was sutured to the root at the level of the sinotubular junction; graft size was chosen according to the patient’s body surface area (<2 m², 22 or 24 mm; 2-2.2 m², 26 mm; and >2.2 m², 28 mm). If aortic root dilatation required RR, a standard technique was applied.16 A Dacron graft was tailored to accommodate the circumferential orientation of the commissures (n = 118); since 2009, 2 symmetric tongues were created (n = 288).

Correction of prolapse of the fused cusp was performed mainly by central plication (593 of 917 [64.7%]). Extensive tis-
sue redundancy, dense fibrosis, or limited calcification required triangular resection (210 of 917 [22.9%]). Prolapse of both cusps required correction in 546 of 917 individuals (59.5%).

In 107 individuals, a very asymmetric commissural orientation combined with only minimal fusion was found. Thus, near-tricuspid morphologic characteristics were present, and the aortic valve was repaired according to the principles of tricuspid AVR.15

Pericardial patches (n = 138) were used for central cusp replacement, closure of defects, or fenestrations. An autologous pericardium was fixed in glutaraldehyde (1.5% for 3 minutes) followed by rinsing in normal saline for 3 minutes. The patch was sutured into the tissue defect using polypropylene sutures (Prolene 5-0; Ethicon).

Annular dilatation (basal ring <26 mm) was initially corrected by subcommissural plication (107 [10.4%]). Since 2009, a suture annuloplasty (591 [57.7%])11 was used to address annular dilatation. It was tied around a graded Hegar dilator according to body surface area (<1.8 m², 21 mm; 1.8-2.0 m², 23 mm; >2.0 m², 25 mm). Also since 2009, in the absence of RR, an asymmetric commissural orientation was modified by sinus plication (138 [13.5%]) to approximate a symmetric configuration. During the past 10 years, we have consistently applied this differentiated anatomic concept in BAV repair.

All patients were followed up clinically and by echocardiography (mean [SD] follow-up, 56 [49] months; maximum follow-up, 271 months). Twenty-four patients (2.3%) were lost to follow-up. The degree of AR was evaluated according to current guidelines,18 and systolic gradients were measured by continuous wave Doppler.18

**Statistical Analysis**

Sample characteristics are expressed as absolute and relative frequencies for categorical variables, mean (SD) values for approximately normally distributed continuous variables, and median values with interquartile ranges for nonnormally distributed continuous variables. Statistical significance testing was conducted using the χ² test for categorical variables and the t test for approximately normally distributed continuous variables.

Cumulative incidences for reoperation or recurrent AR of grade II or higher and associations of preoperative and intraoperative characteristics with respect to time to the first event were assessed in the framework of competing risks to take death into account.19 Statistically significant univariable Fine-Gray models (P < .01) were adjusted for covariates that altered crude effect estimates by more than 10% and were considered clinically relevant. For fitted (multivariable) Fine-Gray models, the proportional subdistribution hazards assumption was assessed using (scaled) Schoenfeld residuals.20 Overall survival was analyzed in a similar fashion using the proportional hazards model. Expected survival for an age- and sex-matched general population was estimated using a suggested approach21 and life tables from the Federal Statistical Office of Germany.

The significance level was set at P < .05, and reported 2-sided P values were not adjusted for multiple comparisons owing to the explorative nature of this investigation. All analyses were conducted using the cmprsk, stats, and survival packages in R, version 3.5.1.22,23

**Results**

Among the 1024 patients in the study, the mean (SD) cardiopulmonary bypass time was 70 (30) minutes, and the cross clamp times was 49 (22) minutes. Twenty-two patients (2.1%) required reexplanation for hemorrhage. Thromboembolic strokes were observed in 1 patient (0.1%) during the hospital stay and in another 7 patients (0.7%) during follow-up. All late strokes occurred in the context of paroxysmal atrial fibrillation.

Postoperatively, transvalvular gradients were significantly higher after repair of asymmetric BAVs without commissural modification (mean [SD], 12 [10] mm Hg; mean [SD] peak, 23 [17] mm Hg) compared with symmetric or modified asymmetric BAVs (mean [SD], 7 [4] mm Hg; mean [SD] peak, 12 [7] mm Hg; mean gradient, P = .02; maximum gradient, P = .01). At hospital discharge, significantly decreased left ventricular dimensions were observed compared with the preoperative size (mean [SD] left ventricular end-systolic diameter, 41 [7] mm; mean [SD] left ventricular end-diastolic diameter, 54 [7] mm; P < .001) (Table 1).

**Survival**

Four patients (0.4%) died during the hospital stay, while another 40 individuals died during follow-up, for a 15-year survival of 82.1% (Figure 2A). The following results summarize estimates for 10-year and 15-year survival. Reported P values refer to comparisons of hazard functions between groups and were derived from the log-rank test.

Patients whose operation was performed with the anatomic repair concept showed a significantly superior 10-year survival compared with patients whose operation was performed prior to 2009 (98.7% vs 87.6%; P < .001) (Figure 2B). Ten-year survival was also better among patients without cardiac comorbidities (92.9% vs 84.3%; P = .02) and after the addition of annuloplasty (98.7% vs 88.7%; P = .001).

At 10 years, the survival rate was lower after the use of a pericardial patch (80.6% vs 93.3%; P < .001) among patients with limited cusp calcification (86.9% vs 92.2%; P = .03), and after tricuspid-like repair compared with all other orientations (10 years, 55.6%; P < .001). After adjustment for potential confounders, a strong association was found for the use of a pericardial patch (hazard ratio, 2.95; 95% CI, 1.43-6.11; P = .003). No association was found for preoperative left ventricular end-systolic diameter (hazard ratio, 0.99; 95% CI, 0.95-1.04; P = .74) or left ventricular end-diastolic diameter (hazard ratio, 0.97; 95% CI, 0.93-1.00; P = .08).

**Reoperation**

A total of 101 patients required reoperation on the aortic valve, of whom 32 underwent re-repair. Of the 101 patients who required a reoperation, 72 had undergone surgery without the differentiated anatomic repair concept. The cumulative
The incidence of reoperation was 19.8% (95% CI, 15.0%-24.7%) at 10 years and 30.7% (95% CI, 22.7%-38.7%) at 15 years.

The following results summarize the estimates of cumulative incidence for reoperation at 10 and 15 years. Reported P values refer to comparisons of cumulative incidence functions between groups and were derived from the Fine-Gray test.

The cumulative incidence of reoperation at 10 years was significantly lower among patients who underwent surgery since 2009 with the current repair concept compared with those who had undergone surgery in the earlier period (8.8% vs 24.6%; P < .001) (Figure 3A). For patients who underwent surgery prior to 2009, the 10-year incidence of reoperation was lower after RR compared with AVr (10.2% vs 35.0%; P < .001), while there was no difference after 2009 in reoperation rates between RR and AVr among patients who underwent surgery with the anatomic repair concept. The incidence of reoperation at 10 years after RR was not altered by the addition of annuloplasty (5.8% vs 9.6%; P = .50), but a decreased incidence of reoperation at 10 years was observed for AVr after the addition of annuloplasty (5.9% vs 22.4%; P = .01).

The factors associated with an increased incidence of reoperation included use vs no use of a pericardial patch (55.0% vs 11.0% at 10 years; P < .001) (Figure 3A). For patients who underwent surgery since 2009 with the current repair concept, presence or absence of cusp calcification (43.7% vs 26.2% at 15 years; P < .001), use vs no use of a subcommissural plication (38.4% vs 27.7% at 15 years; P = .01). Asymmetric orientation...
without surgical alteration was also associated with a signific-
antly higher incidence of reoperation compared with sym-
metric orientation (47.1% vs 18.6% at 10 years; \( P < .001 \)).

The cumulative postoperative incidence of severe aortic
stenosis was 4.2% at 10 years and 10.6% at 15 years. It was
higher among patients showing cuspal calcification at the
time of surgery (11.6% at 10 years and 15.2% at 15 years) compared
with individuals without cuspal calcification at the time of sur-
gery (1.5% at 10 years and 8.8% at 15 years; \( P = .02 \)). After ad-
justment for potential confounders, strong associations re-
mained for cuspal calcification (subdistribution hazard ratio
[SHR], 1.79; 95% CI, 1.23-2.59; \( P = .01 \)), pericardial patch (SHR,
5.25; 95% CI, 3.52-7.82; \( P < .001 \)), and asymmetric commis-
sural orientation (SHR, 1.95; 95% CI, 1.02-3.72; \( P = .04 \))
(Table 2).

Reoperations associated with annuloplasty were neces-
sary for 9 of 591 patients (1.5%) for lateral wall ischemia ow-
ing to occlusion of the circumflex artery requiring subse-
quent removal (n = 4) or closure of a ventricular septal defect
caused by erosion of the membranous septum (n = 5). Those
complications occurred in the early phase of the technique and
were not seen in the last 350 patients. Two patients required a
postoperative pacemaker implant owing to complete atrioven-
tricular block.

**Recurrent Aortic Regurgitation**

The cumulative incidence of recurrent AR of grade II or higher
was 24.6% (95% CI, 19.8%-29.4%) at 10 years and 30.8% (95% CI,
23.8%-37.8%) at 15 years. It was lower for patients who un-
derwent RR primarily for aneurysm and without severe pre-
operative AR (8.9% at 10 years and 13.0% at 15 years) com-
pared with patients with severe preoperative AR undergoing
either AVR (29.7% at 10 years and 34.3% at 15 years) or RR (24.6% at
10 years and 32.7% at 15 years; \( P < .001 \)).

Preoperative severe AR was associated with time to recur-
rent AR of grade II or higher (SHR, 1.96; 95% CI, 1.25-3.06;
\( P = .003 \)). Recurrent AR was also associated with the operative
covariate use of a pericardial patch (SHR, 3.10; 95% CI, 2.16-
4.47; \( P < .001 \)) and the use of the eH measurement (SHR, 2.16;
95% CI, 1.19-3.91; \( P = .01 \)), along with the presence of cuspal
calcification (SHR, 1.79; 95% CI, 1.23-2.59; \( P = .002 \)).

Prior to 2009, RR was inversely associated with time to re-
current AR (SHR, 0.46; 95% CI, 0.28-0.76; \( P = .003 \)), while there
was no association after 2009 with the current repair con-
pcept. After adjustment for potential confounders, associa-
tions remained for use of a pericardial patch (SHR, 3.10; 95%
CI, 2.16-4.47; \( P < .001 \)), preoperative severe AR (SHR, 1.88; 95%
CI, 1.17-3.02; \( P = .009 \)), primary indication (aneurysm com-
pared with AR: SHR, 0.37; 95% CI, 0.23-0.62; \( P < .001 \)), and
cuspal calcification (SHR, 1.68; 95% CI, 1.10-2.57; \( P = .02 \)).

**Discussion**

With the development of heart valve prostheses in the 1960s, aor-
tic valve replacement became the standard treatment for AR. It became apparent that, at 10 years, a proportion of the
patients had developed valve-related complications. Twenty-four
Valve-related mortality was observed, which was associated with
reduced life expectancy after aortic valve replacement. Twenty-five In addition, there exists the need for reoperation, even after me-
chanical prosthetic replacement. Twenty-six Moreover, many young
patients do not wish to undergo anticoagulation. For these rea-
sions, AVR appears as a promising alternative to replacement.
A possible positive association between valve repair and sur-
vival has been proposed in a very limited cohort of patients. Twenty-eight The current results indicate that survival after AVR is similar
to the estimated survival of a matched population that expe-
riences very little, if any, excess mortality.

Repair of regurgitant BAVs has been performed for more
than 2 decades. Initially, surgeons relied on a visual assess-
ment of their procedures. Although the early results were

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**Table 2. Associations With Time to Reoperation From Fine-Gray Models**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Crude model</th>
<th>Adjusted model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SHR (95% CI)</td>
<td>( P ) value</td>
</tr>
<tr>
<td>Annuloplasty( ^a )</td>
<td>0.52 (0.32-0.86)</td>
<td>.01</td>
</tr>
<tr>
<td>Commissural orientation( ^b )</td>
<td>3.87 (2.09-7.17)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Tricuspid-like vs symmetric( ^b )</td>
<td>0.93 (0.43-2.03)</td>
<td>.86</td>
</tr>
<tr>
<td>Asymmetric without modification vs symmetric( ^b )</td>
<td>0.79 (0.37-1.66)</td>
<td>.53</td>
</tr>
<tr>
<td>Modified asymmetric vs symmetric</td>
<td>2.44 (1.63-3.64)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Cusp calcification( ^c )</td>
<td>5.25 (3.52-7.82)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Pericardial patch</td>
<td>0.47 (0.31-0.72)</td>
<td>.001</td>
</tr>
<tr>
<td>Root replacement( ^d )</td>
<td>1.84 (1.18-2.88)</td>
<td>.007</td>
</tr>
</tbody>
</table>

Abbreviation: SHR, subdistribution hazard ratio
\( ^a \) Adjusted for chronological age, cuspal calcification, commissural orientation, effective height, pericardial patch, primary indication, and subcommissural plication.
\( ^b \) Adjusted for pericardial patch, primary indication, and root replacement.
good, there was attrition of valve function during later follow-up in several series.6,10,29 Based on the analysis of valve failures, we proposed eH of the valve as an objective and quantitative indicator of valve configuration.8 This observation has been confirmed by others.30 Nevertheless, failures of repaired BAVs continued to occur with frequency.10 In a cohort of more than 300 patients with repaired BAVs, additional anatomic factors associated with valve failure were identified (in particular, annular dilatation),10 which were later confirmed by others.31 Based on these findings, the repair strategy was adapted to the anatomic characteristics of the valve. Probably the most important change was the introduction of the annuloplasty concept for treating annular dilatation. Use of annuloplasty has improved early valve competence,11 and it has also improved the durability of isolated BAV repair.32 This observation could be confirmed by the current analysis. In addition, we have now been able to report a positive association between annuloplasty and survival.

Root remodeling has consistently been associated with the best durability of BAV repair.10 At 15 years, the incidence of reoperation is only 20.0%; the durability is even better if solely recurrent AR is taken as the reason for reoperation (15 years, 10.7%). So far, the addition of annuloplasty to RR has not been associated with any further improvement. This observation indicates that either the annular stabilization is not as important as generally assumed or that RR, in fact, addresses the anatomic annulus33 and may also have an association with the basal plane.33

Local complications associated with the suture annuloplasty were almost exclusively seen early in the experience and with the use of braided polyester sutures. The complications have been largely eliminated using expanded polytetrafluorethylene as the suture material. Thus, our current results for both RR and AVR show a stability that is comparable to that described by others applying an external annuloplasty ring34 or using a valve reimplantation more liberally.35

More important, we found that an asymmetric configuration of the valve is associated with decreased stability10 and increased turbulence in the ascending aorta.36 We showed that modifying commissural orientation close to a symmetric design was associated with improved systolic valve function and repair durability.13,14 In the current analysis, patients with an unchanged asymmetric commissural orientation were associated with a higher incidence of reoperation as well as higher postoperative transvalvular gradients, thus confirming earlier findings.13,14

There is a low 15-year postoperative incidence of calcific aortic stenosis of 10.6% despite calcific plaques being present at the time of initial surgery in more than 50% of patients. With these calcium deposits, the 15-year incidence of valve stenosis was only 15.2%, still comparing favorably with bioprostheses in a similar age group. In the absence of calcium deposits, the incidence of stenosis at 15 years was 8.8%, which implies that noncalcific BAVs may have a high probability of acceptable function at 20 years and beyond. Despite the initial enthusiasm about excision of calcium with partial cusp replacement using the pericardium, the stability of this modification was disappointing, with a high incidence of early reoperation. Although resection of limited plaques with direct approximation of cusp tissue seems to be an acceptable approach, the use of the pericardium for cusp replacement should be avoided, and such valves should be replaced.

The current data seem to confirm the clinical relevance of the factors associated with valve failure identified previously.10 More important, they confirm the applicability and stability of the anatomy-based repair strategy, and we have described the stability of the repair up to 10 years, which is significantly superior to the stability described in early experience. Using this concept, we are now able to achieve a stable repair result for most patients.

Limitations
The present study has certain limitations owing to its retrospective and monocentric design because it does include modifications introduced over time. Nevertheless, surgical bias is probably limited by the fact that one surgeon (H.-J. S.) substantially participated in all procedures.

Moreover, our findings need to be interpreted with caution owing to multiple testing and the size of different subgroups. Despite the adjustment for possible confounders, residual confounding may have been present.

Nonetheless, to our knowledge, this is the first study on BAV repair incorporating a population of more than 1000 participants with a follow-up now reaching 24 years. Nonetheless, all long-term observations must be carefully interpreted owing to the fact that only a limited proportion of patients had a follow-up longer than 10 years. Longer follow-up will be necessary to evaluate the true long-term durability of BAV repair.

Conclusions
This study suggests that BAV repair has excellent durability if all pathologic components of the aortic valve and root are addressed by an anatomy-based repair concept. Survival after BAV repair is greater than 80% at 15 years and similar to the expected survival of the general population. If partial cusp replacement is required or cusp calcification is present, valve replacement should be preferred.


