Valve-sparing aortic root replacement: Strategies to avoid residual aortic regurgitation

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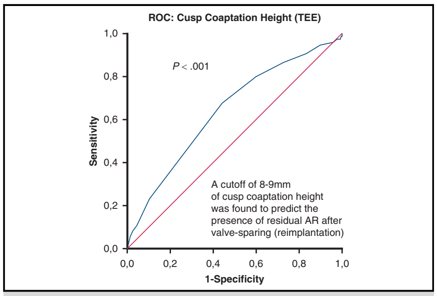
ABSTRACT

Objective: The study objective was to identify quantitative criteria to avoid residual aortic valve regurgitation after valve-sparing aortic root replacement.

Methods: Between 2016 and 2023, 738 adult patients were recruited into the German Aortic Root Repair Registry. A total of 562 patients with datasets on aortic root measurements and tricuspid valve treated with reimplantation valve-sparing aortic root replacement were selected. End points were any grade of residual aortic valve regurgitation and postrepair coaptation height. Tested variables included procedural and anatomic characteristics, including length of cusp margins and geometric cusp heights.

Results: The optimal classifier predicting freedom from residual aortic valve regurgitation was cusp coaptation height 8 to 9 mm or more (sensitivity = 0.7-0.8). Annular downsizing alone was not useful to predict residual aortic valve regurgitation (P = .472, 95% area CI, 0.414-0.54). Patients with a mean free margin length of at least 45 mm and a sum of free margin lengths of at least 125 mm were more likely to present coaptation heights of at least 10 mm (R2 0.038, P = .006).

Conclusions: The target coaptation height after valve-sparing aortic root replacement should exceed 8 to 9 mm. Chances of achieving it can be estimated on the basis of a measurement of cusp quantity. If in doubt when inspecting a valve, numerical criteria can help with surgical decision-making in favor of or against a valve-sparing approach. (JTCVS Open 2025;24:85-95)



ROC on predictive value of postoperative coaptation height on the presence of residual AR.

CENTRAL MESSAGE

A coaptation height of more than 8 to 9 mm is optimal in terms of avoiding rAR after the David operation. Strategies based on quantifiable parameters can facilitate the decision in favor of or against a valve-sparing approach.

PERSPECTIVE

GEARR is a registry with a highly selected and homogenous patient substrate who underwent operation in recent years (2016-2023) to avoid era effects. The fate of rAR and different variants of the David V-SARR in the long term are objectives of future studies.

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Abbreviations and Acronyms

- AR = aortic regurgitation
- CPB = cardiopulmonary bypass
- GEARR = German Aortic Root Repair Registry
- rAR = residual aortic regurgitation
- ROC = receiver operating curve
- STJ = sinotubular junction
- TEE = transesophageal echocardiography
- V-SARR = valve-sparing aortic root replacement

Valve-sparing aortic root replacement (V-SARR) is a durable alternative to prosthetic aortic valve and root replacement for patients with aortic root aneurysms.[1] Residual aortic regurgitation (rAR) has been shown to have the potential of progression in the first years after V-SARR and is linked to reoperations.[2,3] The objectives of the study were to find structural and procedural risk factors for rAR after V-SARR in the setting of a tricuspid aortic valve and to identify quantitative valve target values to avoid rAR.

For this purpose, data from the prospective German Aortic Root Repair Registry (GEARR) were screened, which is an intention-to-treat design registry recruiting patients in 6 major cardio-aortic centers. The main inclusion criterion for GEARR is that a patient is scheduled for a full V-SARR (reimplantation only) as the primary plan at the respective center between 2016 and 2024. Participating centers are located in the cities of Leipzig, Munich, Freiburg Bad Krozingen, Lübeck, Hamburg, and Vienna. During V-SARR, a standardized protocol of measurements of the aortic valve and root components was implemented.

The hypotheses underlying the presented data analysis were that (1) cusp coaptation height or cusp effective height cutoff values can be defined, which are linked to a lower likelihood of rAR immediately after V-SARR; and (2) measuring cusp free margin lengths and geometric heights under direct vision during V-SARR can help to predict a sufficient coaptation height after V-SARR and thus help to decide in favor of or against a valve-sparing approach.

MATERIAL AND METHODS

Ethical Statement

The study was approved by the Institutional Review Boards and Ethics Committees of the institutions where the work was carried out (PI institution FR 546/14). Written informed consent was obtained by all patients included in this report.

Patients

Between October 2016 and April 2023, a total of 738 adult patients (mean age 52 years, 83% male) (Table E1) were recruited into the GEARR (DRKS-ID DRKS00007872) in 6 different centers (Figure E1). A total of 562 patients (Table 1) with complete datasets on aortic root measurements and with a tricuspid aortic valve, who were treated with a full V-SARR (reimplantation only) as planned, were selected (Freiburg/Bad Krozingen = 199, Leipzig = 147, Munich = 106, Hamburg = 81, Luebeck = 15, Vienna = 14). End points were any grade of rAR and postrepair coaptation height.

TABLE 1. Basic clinical and surgical data of studied German Aortic Root Repair Registry cohort

Gender (male)	468 (83)
Height (cm)	179 ± 9
Weight (kg)	87 ± 17
Age (y)	51 ± 13
Preoperative NYHA I	201 (36)
Preoperative NYHA II	361 (64)
Preoperative NYHA III	0
Preoperative NYHA IV	0
Graft size [mm]	28 ± 3
Perfusion time [min]	187 ± 64
Aortic crossclamp time [min]	145 ± 44
Valsalva graft	105 (19)
Cusp fenestration present, any number	125 (22)
Cusp repair (plication)	
STJ, preoperative [mm]	44, 44 ± 9
STJ, postoperative [mm]	26, 27 ± 3
Annular diameter (Hegar), preimplantation [mm]	28, 28 ± 2
Annular diameter (Hegar), postreimplantation [mm]	25, 25 ± 2
Annular size reduction [mm]	3, 3 ± 2
Sinotubular:annular size ratio, postreimplantation [mm]	1, 1 ± 0.1
Commissure height, left coronary [mm]	25, 25 ± 4
Commissure height, right coronary [mm]	27, 26 ± 5
Commissure height, none coronary [mm]	27, 27 ± 5
Free margin length, left coronary [mm]	42, 42 ± 7
Free margin length, right coronary [mm]	44, 43 ± 7
Free margin length, none coronary [mm]	43, 43 ± 7
Geometric cusp height, left coronary [mm]	20, 20 ± 4
Geometric cusp height, right coronary [mm]	20, 20 ± 4
Geometric cusp height, none coronary [mm]	22, 21 ± 4

N = 562. n/%, median, mean ± SD. Postoperative STJ diameters are derived from prosthesis sizes. *NYHA*, New York Heart Association; *STJ*, sinotubular junction.

Surgical Technique and Patient Selection

GEARR is a prospective multicenter registry focusing on intraoperative quantitative analysis of the aortic root and valve, as well as long-term results after V-SARR reimplantation procedures. This intention-to-treat design registry focuses on full (meaning all 3 sinuses replaced) V-SARR procedures with the main inclusion criterion being that after evaluation of preoperative imaging, the patient had been scheduled for a V-SARR as surgical "Plan A" in the respective center. Root reimplantation procedures are included exclusively, with all variants of the David operation (I-V) performed according to the individual surgeon's preferences, including both straight grafts and Valsalva grafts (Figure 1). All additional reconstructive procedures on cusps or commissures (eg, plication, closure of cusp defects) are included. Patients with severe preoperative aortic regurgitation (AR) were not actively excluded from this analysis (Figure 2).

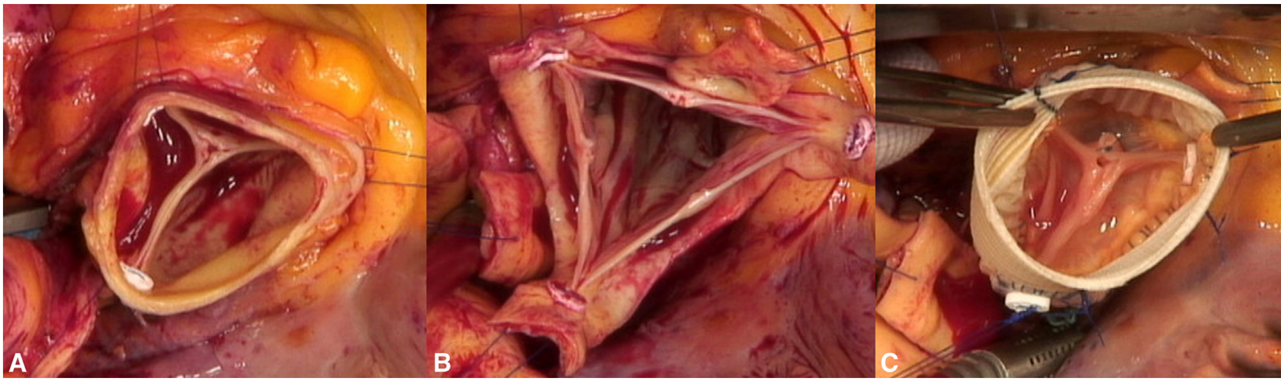

FIGURE 1. Intraoperative photographs of a reimplantation procedure in one of the registry patients. A, After resection of ascending aorta. B, After resection of sinus Valsalva tissue and isolation of coronaries, the 3 cusp free margin lengths can be measured easily by splaying the commissures. C, After reimplantation of the valve inside the vascular graft, cusp reconstruction (shown is central plication of right coronary cusp) is performed and documented.

Intraoperative and Transthoracic Echocardiography Measurements, Definitions

Under direct vision, surgeons performed measurements of geometric cusp heights, which is the distance from a cusp free margin to its insertion line at the lowest point ("nadir") in millimeters (Figure 3). The cusp free margin lengths were measured using a ruler, with the assisting surgeon splaying the respective 2 commissures apart. Annular diameter was measured by Hegar dilator before and after reimplantation of the valve. Neo-STJ diameters were derived from prosthesis sizes. On transesophageal echocardiography (TEE) after cardiopulmonary bypass (CPB), cusp coaptation height (the length of the coaptation line in long-axis view), and effective cusp height (the distance between a virtual line connecting the lowest points of cusp insertion and the tip of the coaptation line, long-axis view)[4] were measured.

Statistics

All statistical analyses were performed using SPSS Statistics 26. Receiver operating curve (ROC) analyses were performed to identify optimal cutoff values for postrepair effective and coaptation heights, resulting in zero or trace rAR (rAR = 0). After this, ROC analyses and curve fitting models were used to define cutoff values of cusp quantity to reach an optimal postrepair coaptation height. Normal distribution of data was examined using the Kolmogorov–Smirnov test.

RESULTS

Three patients (0.5%) needed prosthetic aortic valve replacement within 30 days. Seven patients (1%) had a perioperative stroke, and a permanent pacemaker implantation was needed in 25 patients (4%).

Residual Aortic Valve Regurgitation

Preoperative AR grade was 1.7 ± 1.1 (27% AR grade III), with 60% having a central AR jet, and 40% having an excentric AR jet. Intraoperative post-CPB (TEE) mean AR grade was 0.3 ± 0.5, and within 30 days postoperatively, mean AR grade was 0.3 ± 0.5 (Figure 2). Of the 562 included patients, 148 (26%) left the operating room with any rAR greater than trace. A total of 414 (74%) were documented to have left the OR with grade 0 rAR (no or trace). Subclinical progression of rAR within the first 3 years was detected in 69 patients (47% of the patients with any degree of rAR).

Anatomic Variables and Cusp Quantity

Cusp geometrical heights and free margin lengths were found to be relatively homogenous, with less inpatient variability of geometrical heights (2.5 ± 1.9 mm) and more of free margin lengths (3.7 ± 3.6 mm) (Figure 3). The cusp quantity (expressed as a product) could be modeled as a function of maximum preoperative STJ diameter (Figure 4). Of note, STJ diameters appeared to be relatively small (Tables 1 and E2), although the indication for root or ascending aortic replacement was based on guideline recommendations (Table 2).

Receiver Operating Curve Analysis and Optimal Classifier to Predict Residual Aortic Regurgitation

Figure E2 shows selected results of ROC analyses with the end point of any degree of rAR in the operating room. Most tested variables showed no significant predictive power, among them the preoperative annular diameter (0.968, 95% CI, 0.442-0.561), postoperative annular diameter (0.17, 95% CI, 0.480-0.607), ventriculoaortic junction:sinotubular junction (STJ) ratio, and annular downsizing.

The postoperative cusp coaptation height as measured on immediate post-CPB TEE was found to be of predictive value with regard to avoiding rAR (R = 0.64, standard error 0.037, $P < .005$). An optimum of sensitivity and specificity was determined with a cutoff value of 8 to 9 mm of cusp coaptation height (Figure E2). With a sensitivity of 0.7 to 0.8, the chances of having rAR were higher when postoperative cusp coaptation height was equal to or less than 8 to 9 mm.

Annulus Dimensions and Annular Downsizing

Patients with any grade of rAR had the same amount of annular downsizing when compared with those without any rAR (3.4 ± 2 mm vs 3.6 ± 2 mm). The degree of

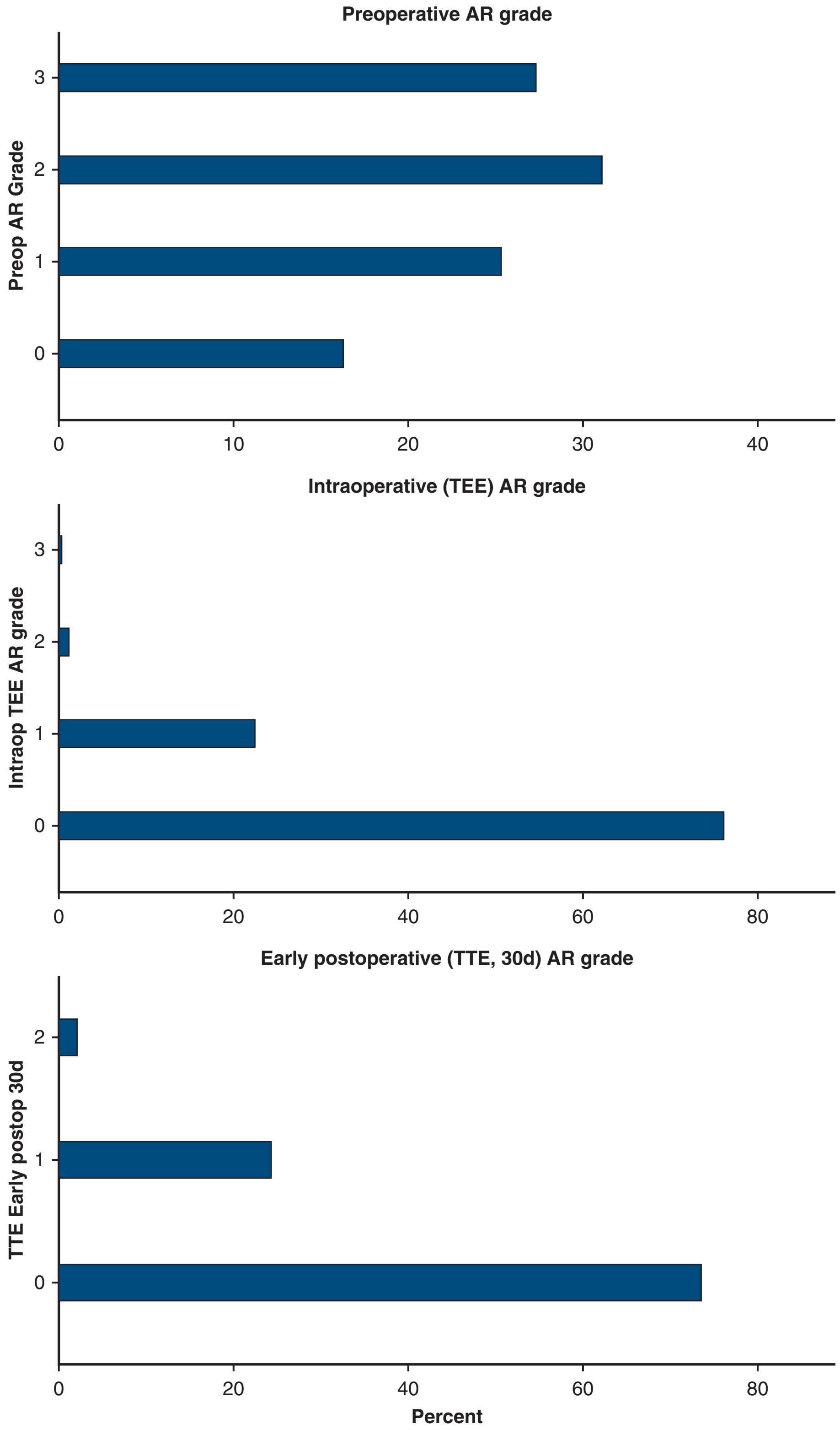

FIGURE 2. Distribution of preoperative and postoperative AR grades. *AR*, Aortic regurgitation; *TEE*, transesophageal echocardiography.

annular downsizing was related to cusp quantity. The larger the average of the 3 cusp free margin lengths in a respective patient was, the more downsizing was done (Figure E3). Most of the patients who left the operating room without any rAR had relatively moderate downsizing of between 2 mm and 4 mm.

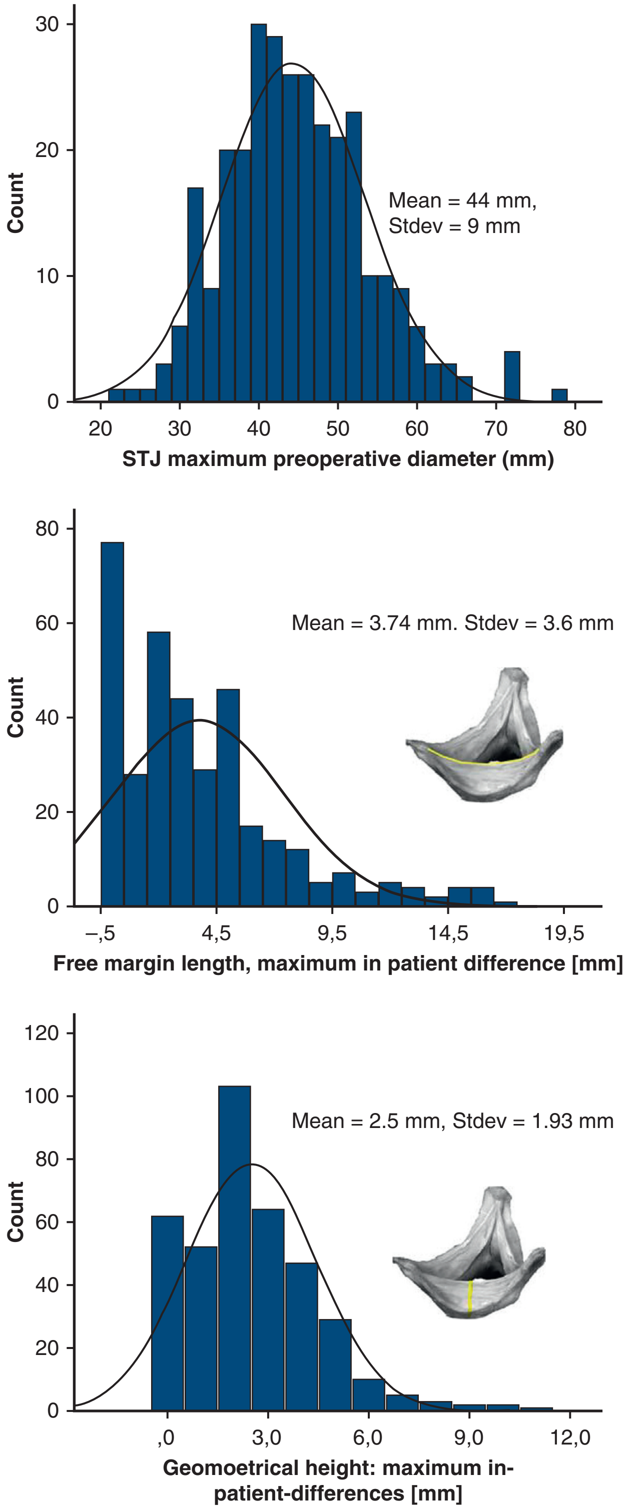

FIGURE 3. Histograms showing maximum STJ diameters preoperatively (*left*) and 2 measures of inhomogeneity of cusp sizes: the maximum difference of the 3 measured free margin lengths (*middle*) and the maximum difference between the 3 geometrical cusp heights. *STJ*, Sinotubular junction.

Sinotubular Junction Dimensions Preoperatively and Postoperatively, Sinotubular Junction Downsizing

The maximum STJ diameter before the operation (mean 44.3 ± 9 mm) tested borderline significant (0.037, 95% CI, 0.502-0.666), and a cutoff value of 41.5 mm of STJ diameter was found to be the optimal classifier value (sensitivity 0.7, 1-specificity 0.557) to predict rAR (Figure E2). The postoperative mean STJ diameter was 26.6 ± 2.9 mm. The larger the preoperative STJ diameter was, the more cusp quantity was available for repair ($P = .002$). Multiple logistic regression analyses did not reveal any statistical significance when STJ downsizing was tested.

Geometric Cusp Height and Length of Cusp Free Margins

The higher the mean of the 3 cusp geometric heights in a patient was, the higher the resulting cusp coaptation height ($t = 3.135$, $P = .002$). A mean geometrical cusp height of 20 mm was needed for a coaptation height of 10 mm (Figure 5). A mean free margin length of at least 45 mm was more likely to result in coaptation heights of at least 10 mm (R2 0.038, $P = .006$, Figure 5).

The mean inpatient variability of geometrical heights was 2.5 mm (SD, 1.9). The sum of the 3 cusp geometric heights of a patient was related to the post-repair coaptation height ($P = .002$). A linear model showed that a minimum of 60 mm sum and a mean of at least 18 mm of geometric heights were needed to achieve a postrepair coaptation height of 10 mm or more (Figure 5).

DISCUSSION

V-SARR procedures are a well-established treatment option,[1,5-9] limiting the cumulative number of life-years spent on coumadin. There is a growing body of evidence indicating that V-SARR procedures tend to be superior to the Bentall procedure with regard to reoperation and survival in propensity-matched analysis,[9-11] which represents the best evidence currently available.

Svensson and colleagues[9] recently showed an 8-year freedom from severe AR of 95% and a 10-year freedom from reintervention of 98%. Arabkhani and colleagues,[10] in a propensity score–matched analysis from the AVIATOR registry, showed better survival (95% vs 85%) and fewer valve-related events after V-SARR compared with prosthetic replacement.

Although some studies suggest that the majority of reoperations after V-SARR might be done for reasons other than aortic valve dysfunction,[8] we consider rAR being worth further research, because some studies have reported progression of rAR within the first postoperative years. Stephens and colleagues[3] reported a progression

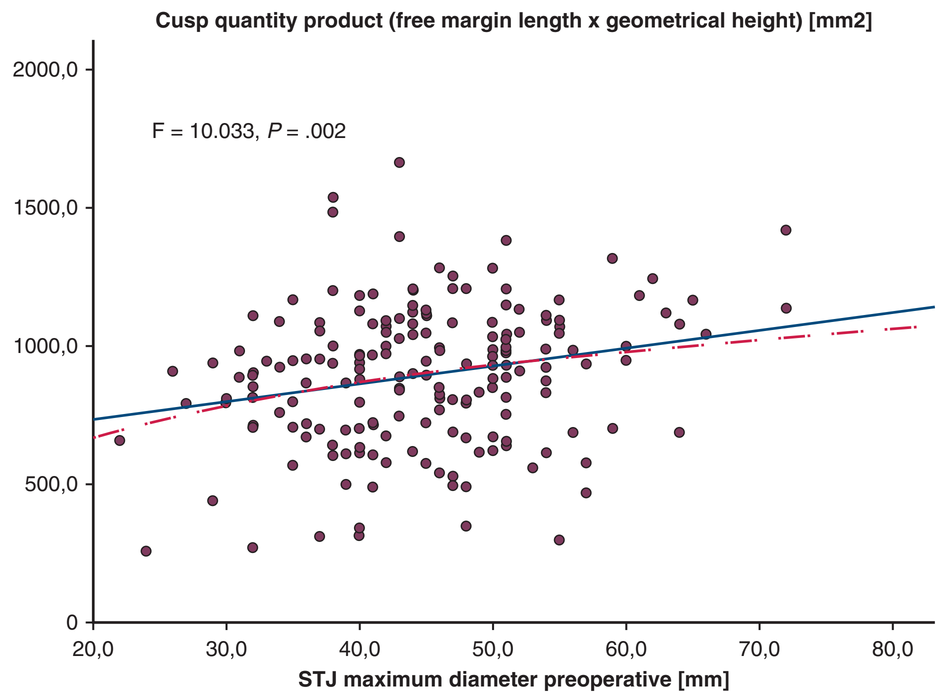

FIGURE 4. Regression showing relationship between the maximum STJ diameter and cusp quantity. *STJ*, Sinotubular junction.

rate of mild rAR to moderate AR in 12% within the first postoperative year, and up to 30% of progression has been reported within the first 4 years.[2]

The number of published studies looking beyond general clinical results and valve function, attempting to clarify the mechanistical details and geometrical

TABLE 2. Quantitative root and valve parameters stratified by residual aortic regurgitation

Measurement	No rAR (max trace)	rAR ≥°I	*P* value
Delta STJ [mm]	18.4 ± 8.4	19.8 ± 8.6	.371
STJ postoperatively [mm]	26.5 ± 2.8	26.6 ± 3.0	.819
STJ Max. preoperatively [mm]	43.4 ± 8.2	46.0 ± 10.0	**.038**
IA_HEGAR preoperatively [mm]	28.1 ± 2.3	28.1 ± 2.7	.840
Hegar (annulus) postoperatively [mm]	24.7 ± 1.7	25.0 ± 2.0	.200
STJ:AVJ postoperatively [mm]	1.1 ± 0.1	1.1 ± 0.1	.970
Delta Hegar (annulus) [mm]	3.6 ± 2.0	3.4 ± 2.0	.567
Fenestrations present (yes/no)	28%	30%	.683
Mean GEOH [mm]	20.8 ± 3.9	20.8 ± 3.9	.974
Sum GEOH [mm]	62.3 ± 11.5	62.3 ± 11.6	.956
GEOH max. in patient difference [mm]	2.4 ± 1.8	2.6 ± 2.1	.513
Sum of FM length [mm]	128.2 ± 19.3	126.7 ± 21.1	.549
Mean FM length [mm]	42.7 ± 6.4	42.3 ± 7.0	.618
FML max. in patient difference [mm]	3.6 ± 3.4	3.4 ± 4.2	.363
Cusp quantity product mm^2 FM length times GEOH [mm^2]	910.3 ± 255.1	884.8 ± 245.5	.417
STJ downsizing:cusp quantity product ratio	0.02 ± 0.01	0.03 ± 0.01	**.044**
STJ downsize:mean FM length	0.45 ± 0.2	0.2 ± 0.24	.134
Cusp effective height TEE [mm]	12.3 ± 3.2	11.5 ± 4.1	.097
Coaptation height TEE [mm]	9.4 ± 2.6	8.2 ± 3.6	**.006**

Mean ± SD. Statistically significant values are bold. *rAR*, Residual aortic regurgitation; *STJ*, sinotubular junction; *Max*, maximum; *AVJ*, aortoventricular junction; *GEOH*, geometric height; *FM*, free margin; *FML*, free margin length; *TEE*, transesophageal echocardiogram.

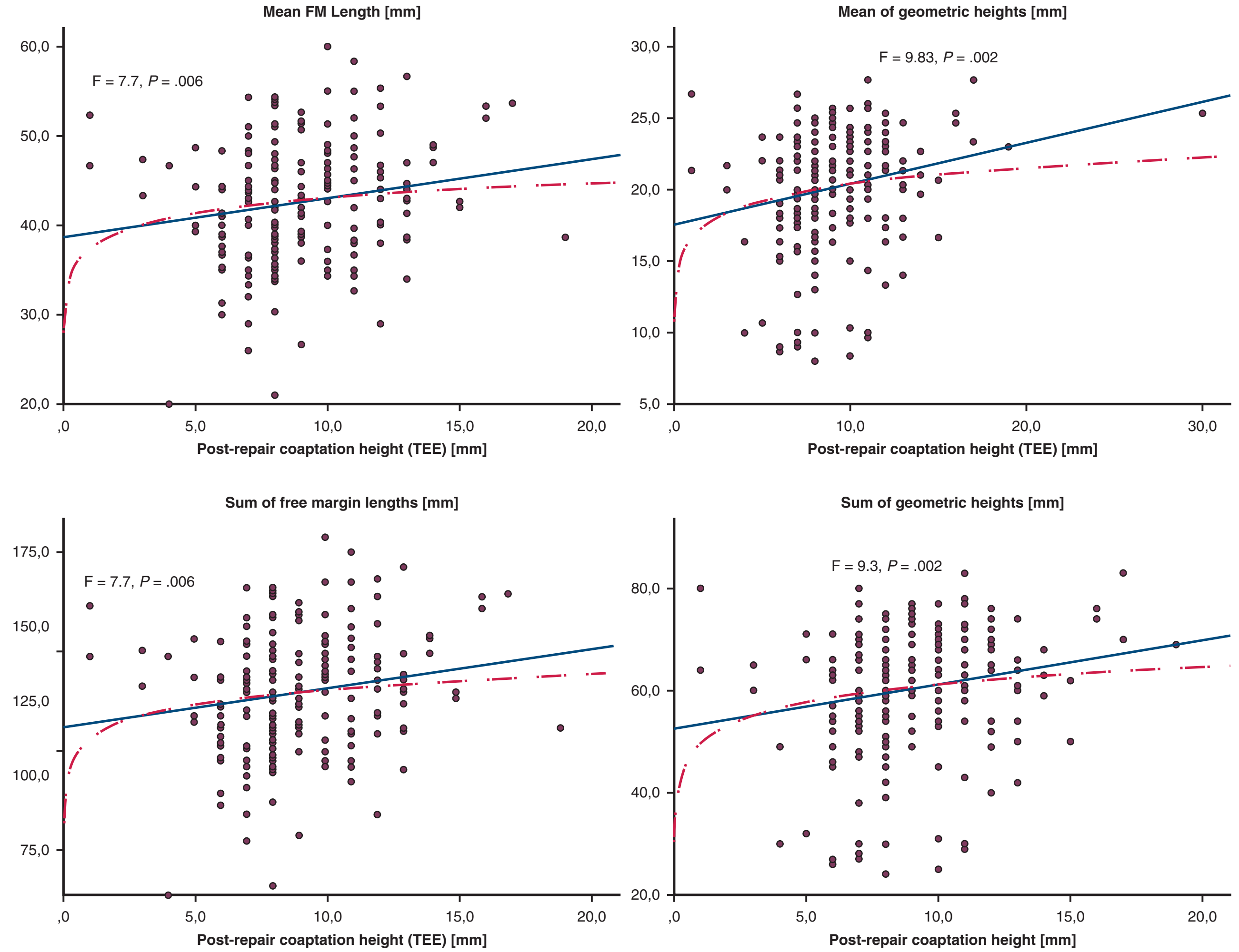

FIGURE 5. The mean and sum of free margin lengths and geometric heights as functions of postrepair coaptation height. *FM*, Free margin; *TEE*, transesophageal echocardiography.

cutoff values behind rAR, are increasing. The focus has been put on cusp effective height by most groups. Kachroo and colleagues,[12] for example, showed that as postoperative effective height decreased below 11 mm, the probability of 2+ or greater aortic insufficiency exceeded 10%. The group of Schaefers (Kunihara and colleagues[4]), although for a different V-SARR technique (root remodeling), reported that freedom from moderate or more AR was 87% versus 76% in patients with more than 9-mm effective height when compared with patients with less than 9 mm (effective height concept). Our data underline that a postoperative coaptation height of 8 to 9 mm is the optimal cutoff value best predicting a low probability of rAR in reimplantation V-SARR.

The data showed that in those patients with rAR grade 0, surgeons had intuitively customized their degree of ventriculoaortic junction downsizing to cusp quantity. Of note, none of the surgeons based such decisions on the intraoperative measurements done for GEARR, and we found relatively small amounts of annular downsizing, which might not reflect the practice of other V-SARR surgeons.

We describe a relatively low rate of additional cusp plication (24%). The need for additional cusp repair, if not needed on the basis of native/preexistent cusp prolapse, is often dependent on the size of the proximal prosthesis, and thus the amount of annular and STJ downsizing, and it is not needed inevitably.

Concept Proposed by the Authors: General Conclusions

The authors are aware that a single or set of quantitative parameters alone should not guide surgical decision making. Nevertheless, we wanted to try and substantiate that some, relatively easy to do, quantitative cusp measurements in the OR should be taken into account because they are linked to postrepair cusp arrangement and the postrepair result.

We propose a goal of 8- to 9-mm coaptation height and a concept of effective cusp quantity. Preoperative routine imaging can give details on cusp quality, but its potential for giving numerical data on geometric cusp quantity (magnetic resonance angiography) has not been explored so far in clinical practice. Free margin lengths and geometrical cusp heights can be measured exactly intraoperatively and might be derived from echocardiography or magnetic resonance angiography.

The chances of achieving a sufficient coaptation height of 8 to 9 mm can be estimated on the basis of a measurement of cusp quantity. The degree of downsizing the aortic annulus, either by choice of prosthesis size or Hegar dilator, should be based on a measure of cusp quantity.

The authors also suggest that more granularity should be used when analyzing late AR, with differentiation among rAR, progress of rAR, and true new-onset late AR, because this differentiation has been made rarely in recent publications, although it has important implications for surgical decision making.

List of Specific Conclusions

The following recommendations refer to adult patients with tricuspid aortic valves and to the goal of achieving a cusp coaptation height 9 mm or more. If in doubt inspecting a valve, these numerical rules might help to decide in favor of or against a valve-sparing approach.

- The average geometrical cusp height in a patient ideally should be 18 mm or more.
- Sum of all 3 geometric cusp heights in a patient should be 60 mm or more.
- Average free margin length in a patient should be 45 mm or more.
- The sum of all 3 free margin lengths in a patient should be at least 125 mm or more.
- Degree of downsizing the annulus should be based on FM lengths and be between 3 and 5 mm.

Different groups have started comparing the variants of V-SARR, such as the use of a Valsava graft versus 2 straight prostheses, as described by Yang and colleagues.[13] The question of the impact of geometrical manipulations especially for BAV is timely, and several groups are interested in it.[14] The late impact of neosinus creation[15] and the use of the Valsalva graft as reported by Weltert and colleagues[5] have to be studied in the future. Singh and colleagues[8] reported on more than 700 David V procedures, which corresponds to a “handmade” neo-STJ, and showed the wide spectrum of V-SARR variants that have theoretical rheological benefit, but their impact on valve function and reoperation has to be validated. Last but not least, V-SARR procedures have to be proven superior to alternative techniques, such as the Florida sleeve, or other wrapping procedures,[16] such as the PEARS procedure.[17] Alternative grafts such as decellularized homografts[18] and innovative devices for improved intraoperative visualization of results[19] are worth being explored further. With respect to exactly why valves fail after V-SARR, more detailed analyses of modes of failure, as the one by the Homburg group for remodeling cases,[20] will be needed.[21]

Study Limitations

All limitations of a registry study apply. Achieving optimal geometry after a V-SARR should be seen as an important basis, yet the biology of the cusps and local hemodynamics play important roles beyond the achieved short-term success. Some of the anatomic factors described, which are associated with a postoperative coaptation height of greater than 8 to 9 mm, had only minimal statistical significance, and none of the advice given in the article should be seen as a single argument in favor of or against sparing an aortic valve. The decision must take into consideration a number of factors, including the severity and exact mechanism of preoperative AR. We suggest using the numerical advice given as an adjunct only. If one is uncertain whether to attempt a valve-sparing surgery or not, the measurements can be done quickly in the operating room to help with decision-making. It is mandatory to be cautious in overstating the long-term predictive value of the analysis, because this study remains a short-term follow-up study.

CONCLUSIONS

The target coaptation height after valve-sparing aortic root replacement should exceed 8 to 9 mm. Chances of achieving it can be estimated on the basis of a measurement of cusp quantity. If in doubt when inspecting a valve, numerical criteria can help with surgical decision-making in favor of or against a valve-sparing approach.

Conflict of Interest Statement

M.A. is a proctor/consultant/speaker for Edwards, Medtronic, Abbott, Boston, Zoll, AbbVie, and Braun, and received institutional research grants from Edwards, Abbott, Medtronic, and LSI. M.C. is a consultant for TerumoAortic, Medtronic, and Medira, and received one-time speaking honorarium from Edwards Lifesciences Shareholder, TEVAR Ltd, and Ascense Medical. All other authors reported no conflicts of interest.

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

Data Availability Statement

Full data sets are available on request.

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Key Words: aortic root aneurysm, aortic valve repair, valve-sparing aortic root replacement

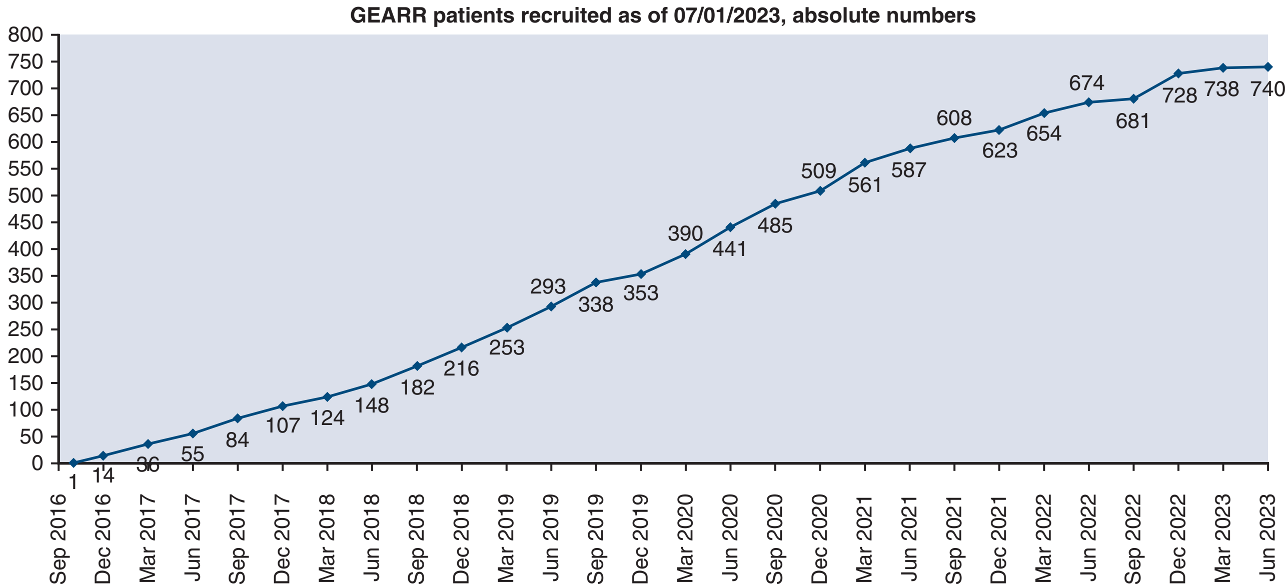

FIGURE E1. Patient recruitment, GEARR, from September 2016 to July 2023. *GEARR*, German Aortic Root Repair Registry.

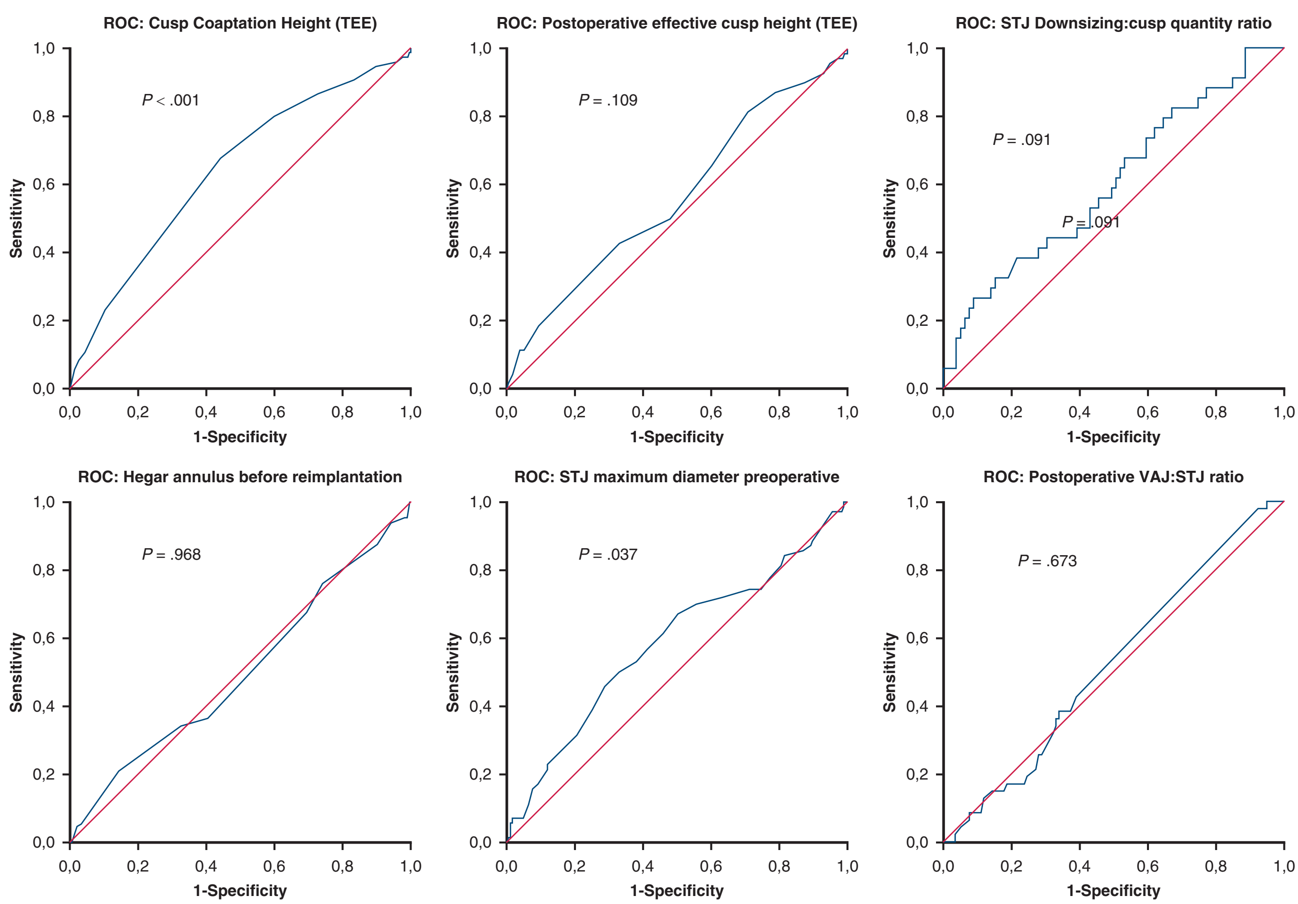

FIGURE E2. Selected test variables, optimal classifier analysis, and end point any grade of residual AR. *ROC*, Receiver operating curve; *TEE*, transesophageal echocardiography; *STJ*, sinotubular junction; *VAJ*, ventriculoaortic junction.

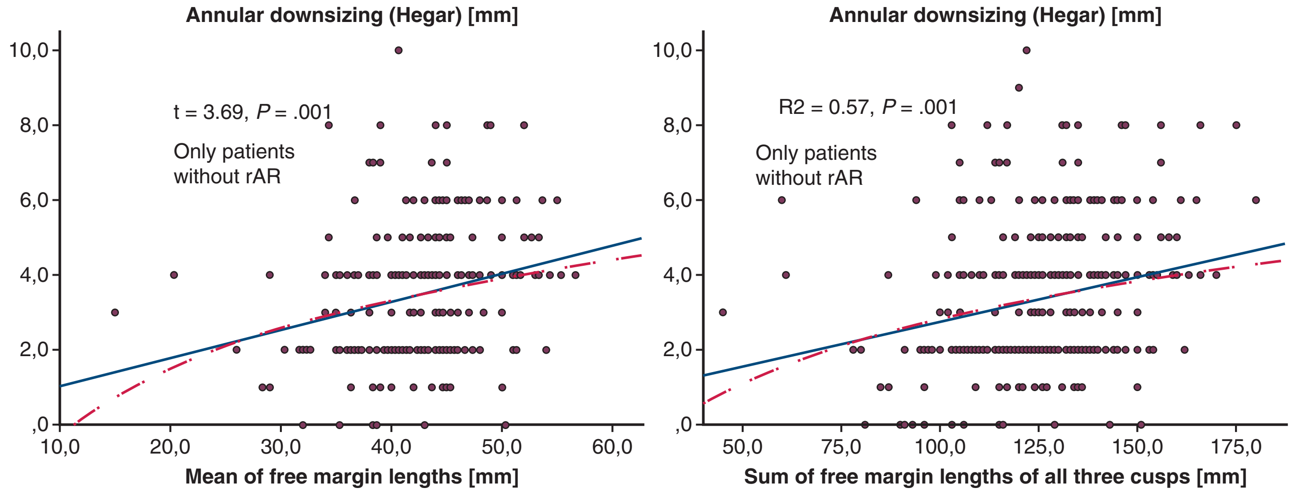

FIGURE E3. Annular downsizing performed as a function of mean and sum of cusp free margin lengths in patients who left the operating room with no residual AR. *rAR*, Residual aortic regurgitation.

TABLE E1. Basic clinical and surgical data of complete German Aortic Root Repair Registry cohort

Gender (female)	138 (19)
Height (cm)	179 ± 9
Weight (kg)	87 ± 18
Preoperative NYHA I	526 (72)
Preoperative NYHA II	152 (20)
Preoperative NYHA III	51 (7)
Preoperative NYHA IV	1 (1)
Bicuspid aortic valve	188 (26)
Connective tissue disease	126 (17)
Acute aortic dissection	38 (5)
COPD	12 (1.6)
Creatinine	0.9 ± 0.3
Prior stroke	26 (3.5)
Prior dialysis	2 (0.2)
Status postendocarditis (not active)	2 (0.2)
Diabetes	9 (1.2)
Prior inotropic therapy	2 (0.2)
Mitral valve repair	33 (4)
Mitral valve replacement	1 (0.1)
Tricuspid valve repair	9 (1.2)
Aortocoronary bypass grafting	53 (7.2)
Perfusion time [min]	187 ± 64
Aortic crossclamp time [min]	145 ± 44
Prosthesis size [mm]	30 ± 2.5
Additional cusp prolapse correction	173 (24)
Raphe resection	18 (2.4)
Commissural reconstruction	24 (3)

N = 730. n/%, mean ± SD. *NYHA*, New York Heart Association; *COPD*, chronic obstructive pulmonary disease.

TABLE E2. Intraoperative measurement results

Variable	Result
STJ maximal diameter preoperatively [mm]	43.9 ± 8.6
STJ maximal diameter postoperatively [mm]	26.7 ± 2.7
STJ downsizing [mm]	17.8 ± 8.3
VAJ preoperative [mm]	28.3 ± 2.6
VAJ postoperative [mm]	24.9 ± 1.9
VAJ downsizing [mm]	3.6 ± 2.2
Difference VAJ:STJ postoperative [mm]	−1.5 ± 2.5
Geometric cusp height LC [mm]	20.3 ± 4.1
Geometric cusp height RC [mm]	20.4 ± 4.1
Geometric cusp height NC [mm]	21.4 ± 4.1
Cusp free margin length LC [mm]	41.2 ± 6.8
Cusp free margin length RC [mm]	43.0 ± 7.2
Cusp free margin length NC [mm]	43.2 ± 7.0
Cusp effective height LC [mm]	11.0 ± 5.0
Cusp effective height RC [mm]	10.8 ± 4.9
Cusp effective height NC [mm]	11.2 ± 5.2

Mean ± SD. Complete cohort. *STJ*, Sinotubular junction; *VAJ*, ventriculoaortic junction; *LC*, left coronary cusp; *RC*, right coronary cusp; *NC*, noncoronary cusp.