0003-4975/$36.00
https://doi.org/10.1016/j.athoracsur.2024.07.010

INVITED EXPERT REVIEW

Aortic Root Remodeling in the Tricuspid Aortic Valve

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ABSTRACT

BACKGROUND Aortic root remodeling is one of the principal forms of valve-preserving root replacement. Its value has been questioned by some, whereas others have achieved excellent valve durability. The purpose of this review is to summarize the existing information to determine which factors may have contributed both to failures and to successes.

METHODS Publications on root remodeling for aneurysm or dissection with tricuspid aortic valves with >15 patients were reviewed for specific details of preoperative and intraoperative management.

RESULTS The series were very heterogeneous. Most operations were performed for root aneurysm, and 10 publications included type A dissection. Connective tissue disease was present in 22% of patients. Mean patient age was 52 years, and 5-year survival varied between 58% and 100%. Most series did not include an annuloplasty. Importantly, no details on quantitative assessment of valve configuration were specified in most series, especially those with suboptimal valve function and durability. The introduction of the effective height concept to control valve configuration was associated with improved results and more frequent correction of cusp prolapse. Late freedom from aortic regurgitation and freedom from reoperation are good in the larger series.

CONCLUSIONS Root remodeling can lead to excellent valve durability if quantitative intraoperative measurement of valve configuration is performed. The addition of an annuloplasty seems to improve aortic valve competence further, even though its effect on durability is not unequivocally proven. The long-term results of root remodeling are good, also in the second postoperative decade, and it is a valid form of valve-preserving root replacement.

(Ann Thorac Surg 2024;118:1005-15)

Aortic root remodeling was introduced to treat aortic regurgitation (AR) in the context of aortic root dilatation. The assumption was that by creating normal root dimensions, valve function would also be normalized and AR would disappear.[1] Long-term results, however, showed recurrence of AR, suggesting that other processes may also contribute to the mechanism of regurgitation.[1] Clinical observations suggested that cusp prolapse may exist in combination with root aneurysm and that its correction by shortening the free margin not only was feasible but was also associated with stable midterm valve durability.[2] At that time, we and others judged valve form visually

The Videos can be viewed in the online version of this article [https://doi.org/10.1016/j.athoracsur.2024.07.010] on https://www.annalsthoracicsurgery.org.

Accepted for publication Jul 15, 2024.

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only, ascertaining that all cusp margins were at equal height.

Subsequently, the analysis of failed aortic valves showed an abnormally low height difference between the annular plane and the cusp free margins.[3] This led to the proposal of using this height difference—named effective height—as an indicator of valve configuration.[4] Normal, adult aortic valves were found to have an effective height of 9 to 10 mm.[5] It appeared that cusps must have sufficient size (geometric height) for an aortic valve to function. Normal values for tricuspid and bicuspid aortic valves were defined.[6] Gradually it became clearer that the anatomical proportions of all individual components of the aortic root are of importance in normalizing aortic valve form and function to achieve a sustainable repair[7,8] (Figure 1). The importance of annular and sinutubular dimensions on aortic valve form was confirmed by computer simulation studies.[9]

Published clinical series with root remodeling, however, have produced mixed results.[1,10-24] Many attributed this to an assumed lack of annular stabilization, and consequently, aortic valve reimplantation became the preferred approach to valve-preserving root replacement by many. We and others continued to practice root remodeling, attempting to systematically identify and correct factors that might lead to valve failure.[1,11,18,20] In this review, we want to highlight the factors that may have been associated with valve failure in the different series and point out important issues that will lead to good results. In view of the influence of valve morphology on technique and results,[3] the focus is on root remodeling in normal (ie, tricuspid) aortic valves.

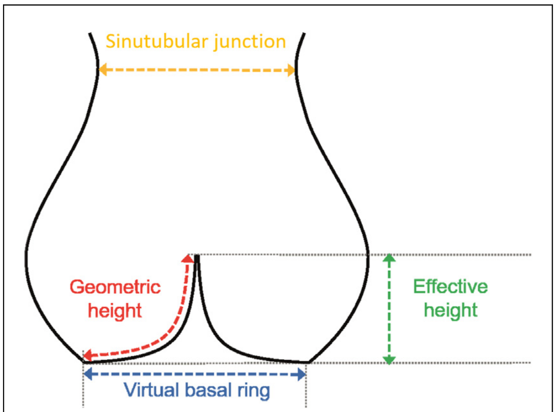

FIGURE 1 Valve configuration is determined by cusp and root dimensions. The sinutubular junction and the virtual basal ring are the important root variables. Geometric cusp height is a surrogate variable for cusp size. Valve configuration can be estimated by effective height. Normal effective height is 9 to 10 mm or 45% to 50% of geometric height.

MATERIAL AND METHODS

Electronic searches for English-language studies on valve-sparing root surgery were made in PubMed/MEDLINE, Embase, and Google Scholar. Search terms included valve-sparing root replacement, aortic root remodeling, aortic root aneurysm, David operation, Yacoub operation, tricuspid aortic valve repair, annulus stabilization, and cusp plication. Reports on the use of the remodeling technique in tricuspid aortic valves with >15 patients yielded 16 publications (Table).[1,10-24] Of articles from the same group, only the most recent was included. From the study of Lansac and colleagues,[18] only the results of tricuspid valves were considered.

RESULTS

We identified 16 publications with results from the years 1979 to 2021. The series are reviewed according to patient selection, operative technique, and survival and functional outcome.

PATIENT SELECTION. Generally, root remodeling has been and is performed as a treatment for root aneurysm, with or without connective tissue disease.[10-12,17-19] It has also been applied in acute aortic dissection type A,[16,21,22] and some series have reported a mix of aneurysm and dissection.[1,13-15,20,23,24] Although root remodeling is mostly applied in adult patients, it has also been used in the pediatric age-group.[1,13,18,23-25] Some excluded roots with a large annulus from undergoing root remodeling,[19,21] whereas many did not specify annular size in their reports.[1,10-14,16,17,21,22]

In most cases, aortic regurgitation was present preoperatively. Variable criteria for severity were used, making comparison difficult. Some classified AR ≥3/4 as clinically relevant,[18,24] others already appreciate AR 2+ as “relevant.”[14,15,22] Whether severe AR may have been excluded from valve preservation is unclear. Mean patient age in the reported series was ~52 years. Yacoub and colleagues[1] and Ehrlich and colleagues[24] included children, and David and colleagues[13] and Lansac and colleagues[18] included teenagers. Most procedures were performed for tricuspid aortic valves.

TABLE Studies Reporting Use of the Remodeling Technique in Tricuspid Aortic Valves

										Results						
	Patients						Methods			Survival		Freedom From				
Authors	Number (% BAV)	Age, y	CTD	AADA	Clinically Relevant AR[a]	Follow-up, mo	Assessment Valve	Annuloplasty (in % Pts)	Cusp Repair	At 5 y	At 10 y	AR >2 at 5 y	AR ≥2 at 5 y	AR ≥ 2 at 10y	Reoperation at 5 y	Reoperation at 10 y
Yacoub et al[1]	158 (1)	47	68 (43)	49 (31)	96 (67)	68	Visual inspection	+ (4)	?	88	79	92	77	75	89	89
Luciani et al[10]	17 (0)	57 ± 11	1 (6)	0	12 (76)	16 ± 12	Visual inspection	–	?	94[b]	?	?	?	?	70[c]	?
Bassano et al[11]	32 (0)	53 ± 19	4 (12)	0	30 (93)	29 ± 20	Visual inspection	–	?	100	?	88	53	?	88	?
Jeanmart et al[12]	48 (23)	54 ± 17	5 (10)	0	20 (42)	50 ± 35	Visual inspection	–	48	87	?	97	?	?	97	?
David et al[13]	61 (3)	49 ± 16	26 (42)	7 (12)	29 (55)	121 ± 53	Visual inspection	–	51	?	?	96[d]	?	?	100[d]	90[e]
Svensson et al[14]	72 (24)	51 ± 16	12 (17)	19 (26)	21 (30)	67.2 ± 48	Visual inspection	–	?	93	87	?	?	?	89	85
Urbanski et al[15]	236 (16)	63 ± 13	9 (4)	30 (13)	?	43 ± 24	Visual inspection	–	?	87	87[f]	95[d]	?	?	?	96[f]
Subramanian et al[16]	51 (2)	62 ± 14	0 (0)	51 (100)	?	?	?	–	?	58	?	?	?	?	92	?
Price et al[17]	29 (?)	36	29 (100)	?	?	100	?	–	?	?	?	?	?	?	86	86
Lansac et al[18]	112 (0)	53 ± 15	26 (23)	0	50 (45)	41 ± 36	Since 2008 use of eH	+	51	?	93[g]	90	87	82	89[g]	84
Klotz et al[19]	101 (22)	56 ± 14.3	12 (12)	0	67 (66)	121 ± 67	Visual inspection	–	31	?	74	?	?	38	?	88
Lenoir et al[20]	83 (31)	48 ± 13	21 (26)	1 (1.2)	28 (36)	43 ± 42	Since 2012 use of eH	+	49	100	99	98	84	?	97	?
Sievers et al[21]	39 (0)	63	2 (6.5)	39 (100)	?	141	Visual inspection	–	?	62	31	?	?	?	83	83
Kato et al[22]	18 (11)	49 ± 14	5 (28)	18 (100)	2 (11)	56 ± 41	Use of eH	+	44	82	?	93	93	?	94	?
Chauvette et al[23]	137 (8)	37 ± 13	137 (100)	4 (3)	29 (21)	60	Since 2008 use of eH	+ (82)	56	98	?	?	83	?	95	?
Ehrlich et al[24]	684 (0)	56 ± 14	64 (9)	72 (11)	467 (68)	86 ± 64	Since 2004 use of eH	+ (52)	83	?	82	?	?	91	?	96

[a]AR 3 or moderate and severe when descriptive classification was used; [b]Results at 3 years; [c]Results at 2 years; [d]Results at 4 years; [e]Results at 12 years; [f]Results at 8 years; [g]Results at 7 years. Data are presented as n (%) or mean ± SD, unless indicated otherwise. AADA, acute aortic dissection type A; AR, aortic valve regurgitation; BAV, bicuspid aortic valve; CDT, connective tissue disease; eH: effective height; Pts, patients.

Three series focused on results of tricuspid valve repair in acute type A dissection,[16,21,22] whereas other series excluded such pathology,[10-12,18,19] In other publications, acute type A dissection was present in 1% to 31% of patients. On average, connective tissue disease was present in 22% of patients.

In most series, valve-preserving surgery has mainly been performed in patients with no or limited comorbidity.[1,10-12,14,17,18,20,22,23] It is currently difficult to judge what an acceptable degree of comorbidity is in order not to increase postoperative morbidity and mortality. In the Homburg experience, no patient was excluded from root remodeling because of a comorbidity. In doing so, age, coronary artery disease, and other valve disease increased early mortality.[24] These were also predictors for increased late mortality, limiting the potential benefit of better durability compared with biological valve replacement.

Most groups tend to be vague regarding their valve-related inclusion and exclusion criteria. Reports include—if at all—qualitative criteria, such as cusp pliability or structural integrity. In 2 series,[19,21] patients with annular size >30 mm were excluded from the remodeling technique but were treated by reimplantation. Only 1 study stated qualitative and quantitative valve indicators.[24] Using minimal geometric height of the cusps of 18 mm as a quantitative indicator, exclusion criteria were cusp retraction, calcification, or multiple fenestrations[26]; in doing so, ~90% of all root aneurysms were treated by valve-sparing surgery.

OPERATIVE TECHNIQUE. The dissection of the root has probably been similar in all series. Although the principal technique of root remodeling has been applied in all series, variations exist, but many reports leave uncertainties. For example, some series include replacement of 1 or 2 sinuses without differentiating the results.[15,16,21]

In the original technique, tongues of predetermined length were cut and sutured into the root starting at the commissures.[27] This approach has been used by at least 1 other group,[18] whereas others may have modified details.

Variability exists regarding choice of graft size. Some have used intercommissural distance[1,10,11,19]; we have chosen graft size according to body surface area, taking a smaller graft for smaller cusps (ie, geometric height of <20 mm).[24] In effect, the graft sizes most frequently used have been 26 or 28 mm. The apparent simplicity confirms the ease of graft size determination commented on by David.[28]

The most important differences exist in assessing postoperative valve configuration. It was not specified in most reports, and one must assume that only visual assessment was used.[1,10-16,19,21] Only 5 series reported intraoperative measurement of effective height using a specific caliper, in 3 in a later part of the series[18,20,22-24] (Figure 2). We have consistently performed this measurement in the past 20 years as basis for cusp repair, which constitutes a relevant difference between our series[24] and others. The type of valve assessment was also associated with the frequency of concomitant cusp repair. Only 8 series report any concomitant cusp repair.[12,13,18-20,22-24] Series that used effective height measurement also had a higher rate of cusp repair.[18,20,22-24] Cusp repair was performed in up to 83% of all procedures in the Homburg series.[24]

The final component of surgical technique relates to the management of annular dilatation. Annular size was determined in 4 publications by intraoperative intubation,[15,18,20,24] but other groups have not reported annular size. Most series did not include an annuloplasty,[10-13,15,19] which also includes the first half of our experience.[24] Yacoub and colleagues[1] added a Dacron (DuPont) band annuloplasty in 6 patients,[1] and Kato and colleagues[22] did so in all their patients. Lansac and colleagues[18] and Lenoir and colleagues[20] started with a Dacron band as annuloplasty in some of the operations

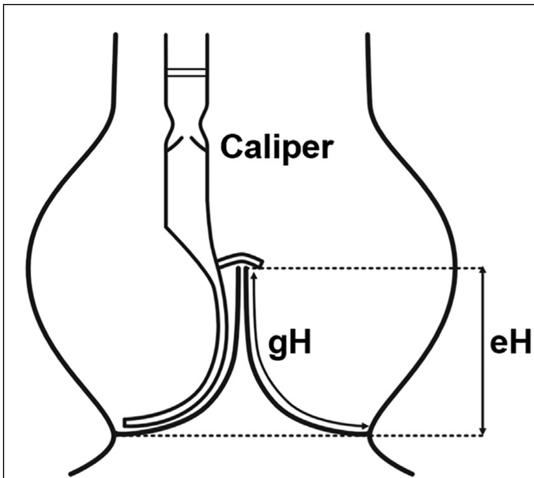

FIGURE 2 Effective height (eH) can be measured intraoperatively with a specific caliper. (gH, geometric height.)

and switched to an expansible annuloplasty ring later for the rest of their series.

In a recent report from our experience, a suture annuloplasty was used in 52% of the total series.[24] Adding a suture annuloplasty to treat annular dilatation appears reasonable based on computer simulation data.[9] On the other hand, annular size reduction has also been seen in the absence of an annuloplasty.[29]

SURVIVAL AND FUNCTIONAL RESULTS. Early results. In-hospital and 30-day mortality has been generally low, (ie, in the range of 0% to 4.6%)[1,10-15,17-20,23,24] Interestingly, also in the setting of acute dissection, a relatively low mortality of 5.6% to 16% was observed.[16,21,22]

Postoperative valve function is difficult to compare between the publications: not all report early postoperative valve function. Some report a proportion of AR ≥2,[10,15] others use AR >2,[24] and 1 study reported the number of procedures requiring a second period of myocardial ischemia.[18] The smaller series from Luciani and colleagues[10] reports freedom from AR >2 at discharge of only 69%, whereas the proportion of residual AR >2 was very low in most series.[11,15,24]

Late results. Late survival has been generally good, with an average survival of 93% at 5 years[1,10-12,14,15,20,23] and 86% at 10 years.[1,14,15,18-20,24] For the series on acute type A dissection, an average survival of 67% at 5 years[15,16,22] and 31% at 10 years[21] is seen.

As in the analysis of the early results, analysis of the late functional results is similarly hampered by different cutoffs for residual regurgitation. In most series,[12,13,15] only AR >2 was reported; in others both AR >2 and AR = 2 were included,[1,11,18-20,24] and some described AR ≥2.[23,24] These differences influence the reported late results: in several series, freedom from AR >2 ranged from 88% to 98% at 5 years.[1,11-13,15,18,20,22] If AR = 2 was included as residual AR, freedom from recurrent AR was only 53% to 87% at 5 years in the larger series.[1,11,18,20] The same holds true for the 10-year results; in our experience, freedom from AR ≥2 was >90%.[24]

Freedom from reoperation as a harder end point is also difficult to compare between the publications because different time points were used. In general, smaller series had less favorable results, with freedom from reoperation at 5 years of 88%[11] or 70% at 2 years.[10] For tricuspid valves, Lansac and colleagues[18] report 10-year freedom from reoperation of 84%, comparable with the results of Svensson and colleagues,[14] Price and colleagues,[17] and Sievers and colleagues.[21] Freedom from operation in other large series ranges between 88% and 90% at 10 years.[1,13,19] Overall freedom from reoperation was 96% in our series.[24] The cumulative incidence of aortic valve-related reoperation at 10 years was 3.2% with effective height measurement compared with 7.6% in the historical controls (ie, without measurement). The addition of an annuloplasty was also associated with marked improvement from reoperation in the Lansac and colleagues[18] series. One must consider that they introduced both the annuloplasty and also effective height measurement at a similar time, making differentiation between the 2 effects difficult. In our experience, the addition of suture annuloplasty improved freedom from reoperation only insignificantly, from 94% to 97%.[24]

COMMENT

REMODELING VS REIMPLANTATION. The initial concept of root remodeling was the restoration of normal root dimensions, assuming that normal aortic valve function would be the automatic consequence.[1] Additional cusp repair was either not considered or not felt necessary. Following the pioneering series,[1] others applied the remodeling concept, while David and Feindel[30] in parallel propagated their technique of reimplanting the aortic valve inside a vascular graft.

In the following years, a relevant proportion of patients with secondary regurgitation after root remodeling was observed,[1,10,11,31] raising skepticism over the general value of root remodeling. Some direct comparisons between the 2 techniques seemed to yield better valve stability with valve reimplantation, and the failures were attributed to the lack of annular stabilization.[31-33] Failures from previous series suggested more reoperations with longer duration of symptoms.[1] Other series suggested cusp pathology as the cause for reoperation.[11,15] Additionally, an increased risk of hemorrhage with remodeling was proposed.

Nonetheless, some positive aspects of root remodeling were found. A clinical study found more physiologic root elasticity with remodeling.[34] In direct comparison, we observed shorter ischemic times with the remodeling technique due to less dissection and suturing. The proposed risk of bleeding could not be confirmed.[23,35] In an in vitro study, physiologic cusp motion was seen only with remodeling, whereas it was pathologic after reimplantation.[36] These observations encouraged some—including us—to pursue applying root remodeling further.

RELEVANCE OF CUSP PROLAPSE. Still, the precise cause of the observed failures was uncertain. Apart from lack of annular stabilization, concomitant and unrecognized cusp pathology was a possible cause, which could have been avoided by better patient selection or added cusp repair. Looking back at the published description of valve assessment or repair in the remodeling series, it is impossible to judge how frequently cusp prolapse was missed. Patient (or valve) selection was not specified, and even the proportion of patients selected for valve preservation remains unknown. The visual assessment apparently used was found to be inadequate in a later series.[37] This possible systematic weakness is also most likely the cause for a relevant incidence of valve failures after valve reimplantation in a recent study.[38,39] In view of these considerations, the results of a recent meta-analysis may be misleading.[33] Not only did this analysis miss some publications reviewed here, no attention was paid to details of operative technique.

Our clinical observations indicated that concomitant cusp prolapse could be present,[2] both with root remodeling and aortic valve reimplantation. Becoming generally apparent only after completion of the root procedure, we repaired it by shortening the free cusp margin rather than converting to composite replacement of valve and root at that stage of the operation. We could indeed achieve stable valve function with such an approach.[2] Further observations revealed that the occurrence of prolapse was likely and caused by the reduction of root size (ie, intercommissural distance).[3] A more systematic investigation of normal aortic valve form was the consequence, leading to the realization that the height difference between annular plane and free margins (effective height) as a configuration indicator followed a constant pattern.[5] A specific caliper was designed to measure effective height intraoperatively, guiding the need for and extent of cusp repair[4] (Figure 2).

By using such a caliper, prolapse could be detected more easily and more frequently, and it facilitated reproducible cusp repair. It also allows for prolapse correction of all 3 cusps if encountered.[24] The control of effective height and the use of the caliper was adopted by others[18,20,22] and has led to marked improvement of aortic valve function and durability.[18] Using the caliper for detection of prolapse, we have encountered prolapse in >80% of all valve-preserving root replacements.[24,26]

Principally, the degree of preoperative insufficiency correlates with the frequency of cusp prolapse.[40] By preserving aortic valves with lesser degrees of regurgitation, the surgeon can expect less prevalence and extent of prolapse. An eccentric jet indicates asymmetric cusp pathology, and a prolapse in most instances.[26] A central jet, however, does not exclude prolapse, because the stretching of cusp tissue may be "masked" or compensated through the increased intercommissural distance of the root aneurysm.[26] Thus, the surgeon must be prepared for cusp prolapse and be familiar with its detection and management. In detecting it, the use of the caliper has been extremely helpful. Although the proportion of patients treated by valve preservation has been limited even in experienced centers,[41,42] we have been able to preserve up to 90% of valves in the context of a root aneurysm.[26]

SURGICAL INDICATIONS. The indications for prophylactic root replacement are established.[43] Root replacement as remodeling also appears advisable with lesser degrees of dilatation (<42 mm) if the operation is performed for severe and prognostically relevant AR. Most procedures were performed for tricuspid aortic valves. Bicuspid valves were also included (1%-31% of patients) in 10 series.[1,12-16,20,22,23] With the latter morphology having a different natural course, the results of those series with a large proportion of bicuspid valves[12,14,19,20] have to be interpreted more carefully. Bicuspid valves require a modified concept.[3]

TECHNICAL CONSIDERATIONS. The surgical technique remains generally standardized. An important prerequisite is assessment of valve configuration under near-physiologic circumstances (Supplemental Video 1). To mimic the pressurized conditions of the aortic root necessary for normal cusp configuration, we systematically apply tension on the commissures in an upward and outward direction. The feasibility of cusp repair depends on absence of cusp retraction to have sufficient tissue. This was generally acknowledged by Yacoub and colleagues,[1] but only defined later. In view of the poor results of repair with retracted cusps,[44,45] geometric height is measured in each cusp from the nadir to the central cusp free margin to ascertain a minimum of 18 mm in all 3

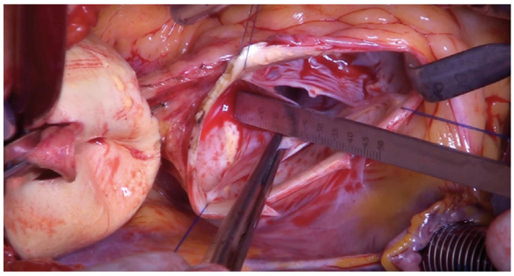

FIGURE 3 Aortic root exposure and geometric height measurement. The aorta is transected above the sinu-tubular junction, and stay sutures are placed above each commissure. The geometric height of each cusp is measured with a ruler, and the cusps are carefully assessed visually.

cusps (Figure 3). Cusp pathology must be clearly defined. Perforations may be closed with a pericardial patch, and fenestrations may be tolerated if not involved in the prolapse; otherwise, they can also be closed with a patch.[46] In the presence of large fenestrations or calcifications, the valve will likely benefit from replacement.

Graft sizing can be simplified. The principle of the operation is to create a root size in which the valve will be large enough to seal it in diastole. A smaller valve (common in smaller patients) thus requires a smaller graft. In our experience, a 26-mm graft has accommodated most valves with good postoperative function. Interestingly, other series came to a similar conclusion.[12,13,15,22] If the patient is small (we have chosen a 2 m^2 body surface area as the cutoff) or the valve is smaller (geometric height <20 mm), we have empirically chosen a smaller graft. For larger cusps (geometric height ≥22 mm), a 28-mm graft may be appropriate. Graft tailoring does not require much precision (Supplemental Video 2).

Care must be taken to avoid height restriction of the commissures.[47] We have been able to avoid this problem, which otherwise could lead to irreversible distortion of the valve. After generating the tongues, we have always started suturing in the nadir of the sinuses and continued toward the commissures. With intention we have attempted to bring more graft/tongue length into the sinus by "cheating," (ie, having a wider distance between the suture bites on the graft than on the remnants of aortic wall). The resulting excess length of the graft tongue will contribute to sinus bulging and will also minimize the chance of commissural height restriction (Figure 4; Supplemental Video 3).

In valve and root assessment, one must consider the need for annular size reduction. Because of the oval shape, echocardiographic assessment may underestimate its true diameter. We always double-check the annular diameter by intubation with a Hegar dilator or other standardized sizer, and we often find a discrepancy between the 2 measurements. The limitations of 2-dimensional transesophageal echocardiography can be minimized by postprocessing of data sets obtained by 3-dimensional echocardiography.[48,49] Although there seems to be consensus about the stabilizing effect of annuloplasty in isolated bicuspid valve repair,[50] the benefit of annuloplasty as an adjunct to root remodeling is less obvious.[51]

Computer simulation studies on a tricuspid aortic valve have shown a negative effect of annular dilatation on valve configuration.[9] With increasing annular size, effective height and—importantly—coaptation height decrease.[9] Thus, it appears as logical to correct any annular dilatation by annuloplasty, using a dedicated ring[18] or as suture annuloplasty[24] (Figure 5; Supplemental Video 4). On the other hand, annular size reduction has been observed with root remodeling alone and without annuloplasty.[29]

The first publication on the value of an annuloplasty seemingly showed a marked positive effect with implantation of a Dacron ring.[18] The evidence, however, is not as clear as it appears. In that publication, the historical series had poor valve durability, markedly worse than our experience without an annuloplasty, suggesting a learning curve effect. More importantly, the surgeons started to measure effective cusp height systematically at the same time they implanted a ring.[18] Our more recent experience may provide clearer evidence on the effect of an annuloplasty.[24] The addition of a suture annuloplasty led to less residual regurgitation early (despite a high proportion of patients requiring concomitant cusp repair). AR was less mid- to long-term, whereas we have not (yet) observed an improved freedom from reoperation up to 14 years.[24] Nonetheless, the annuloplasty will increase coaptation height and thus likely compensates for inaccuracies in cusp repair.[9] Weighing pros and cons, an annuloplasty should probably be added to root remodeling, and this is our current routine with tricuspid aortic valves.

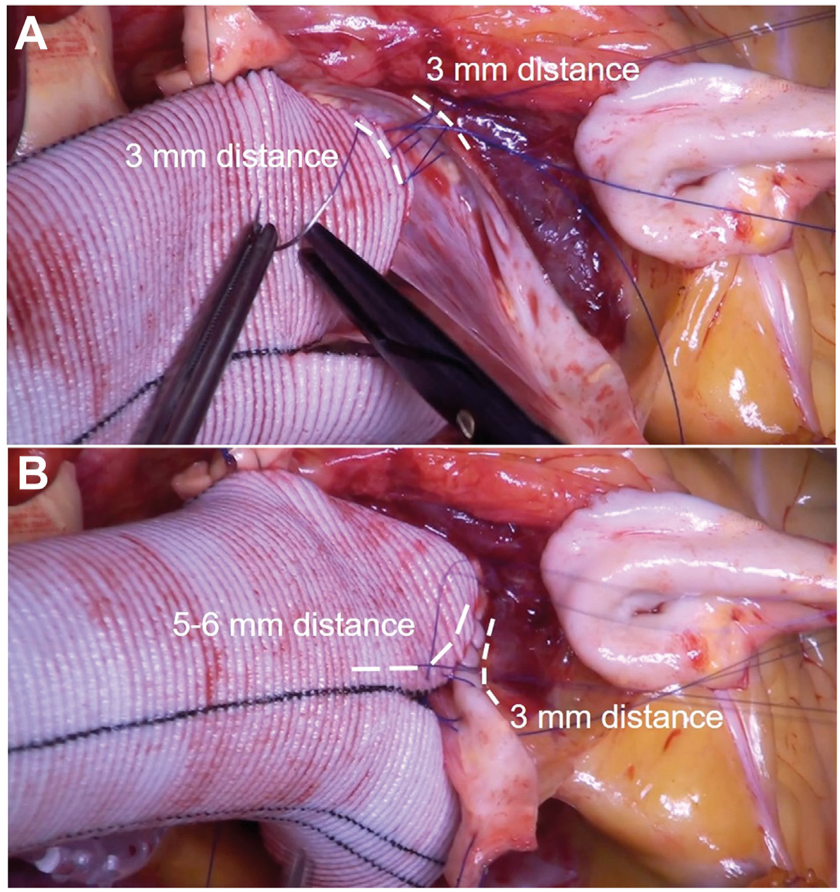

FIGURE 4 Suturing of the graft. (A) Close to the nadir, equal distance between the stitches (~3 mm) is maintained for graft and aortic wall remnant. (B) As the suture approaches the commissure, the distance between stitches is increased to 5 to 6 mm on the graft, keeping the 3 mm distance on the aorta. This places more graft length into the sinus and avoids restriction of commissural height.

Surgical technique starts with evaluation of feasibility of cusp preservation and ends with correction of cusp pathology as the final component of the procedure, cusp prolapse being the most frequently associated lesion.[11,26] Visual assessment compares the relative height of the 3 free cusp margins, which should be at the same level. Although we also use visual assessment, we have additionally measured the effective height of each cusp in the past 20 years.[24] The effective height of each cusp is the result of free margin length and respective intercommissural distance, and any root replacement will reduce intercommissural distance. Thus, effective height must be assessed after normalizing intercommissural distance (ie, after completion of root remodeling) (Supplemental Video 5). In the long-term, cusp prolapse, as defined by effective height, proved to be a predictor for late recurrence of valve regurgitation and was often underestimated by visual assessment.[35] Absence of effective height measurement most likely explains the suboptimal results of previous series, in most of which no quantitative measurement was performed[11,13,19]; it might be a predictor for poorer valve durability.

Normal effective height is 9 mm to 10 mm; for larger or smaller cusps it is 45% of the geometric height. Prolapse can thus be defined as a subnormal effective height; if present, it can easily be corrected by shortening the free margin using a 5-0 or 6-0 polypropylene suture (Supplemental Video 6). In cases of marked tissue redundancy, the plicating sutures may be continued into the belly of the cusp to avoid postoperative billowing. We have used this concept for >25 years and have not seen adverse effects. The systematic use of the caliper has led to more cusp repairs than in other series while ensuring excellent mid- and long-term results.[24]

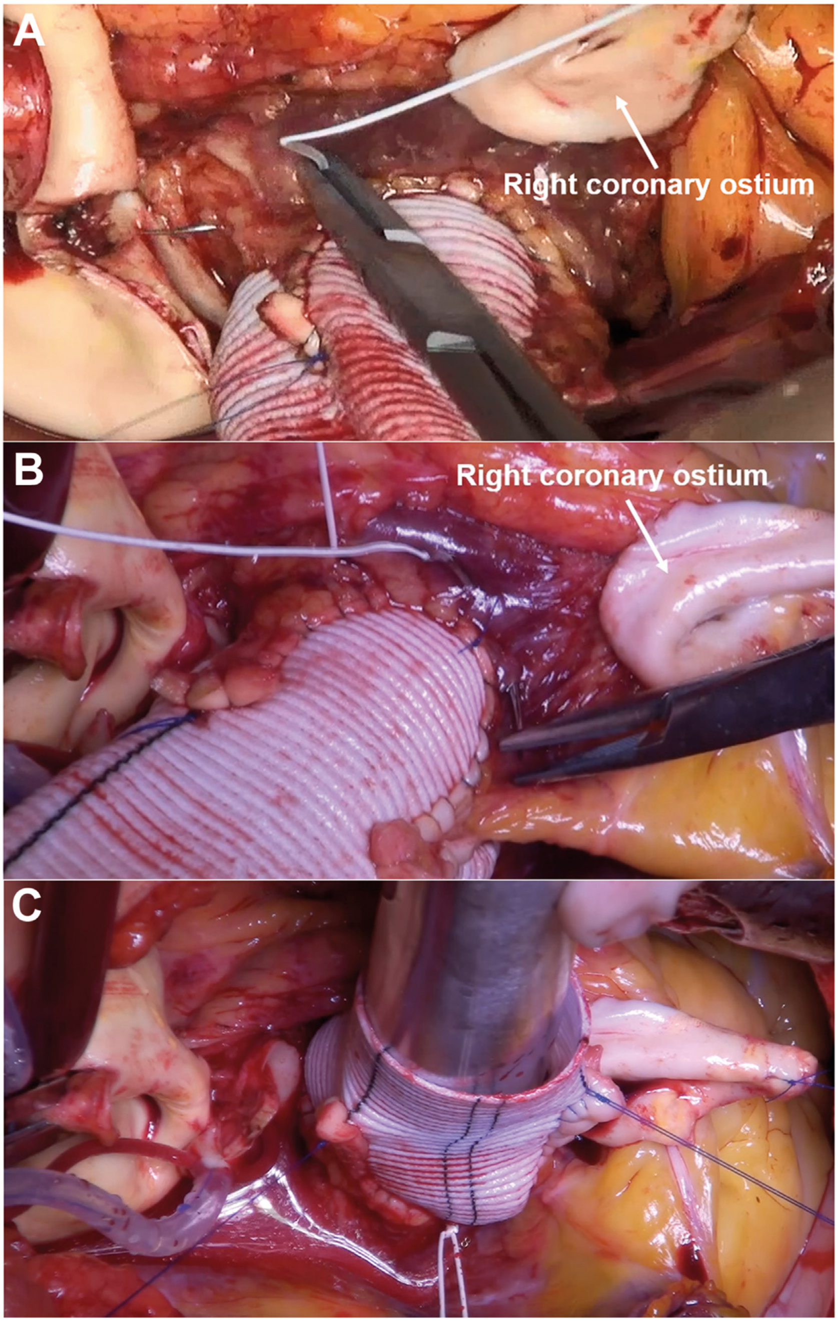

FIGURE 5 Suture annuloplasty. (A) By pulling the graft upwards, the base of the repaired root is easily visible. A double-armed polytetrafluoroethylene (Gore-Tex CV-0; W. L. Gore and Associates, Munich, Germany) suture is placed through septal tissue outside the left/right commissure. (B) Anteriorly, the needle is passed through the tissue at the nadir of the replaced right sinus and then tangentially at the base of the noncoronary sinus. The other arm is passed posteriorly in identical fashion. (C) The suture is tied around a Hegar dilator of predetermined size.

CONCLUSION. Root remodeling as one of the 2 main forms of valve-preserving root replacement continues to be a valuable option for many patients with root aneurysm and variable degrees of regurgitation. Because valve form and function depend not only on root size but also on cusp configuration, its sole use will rarely suffice in creating normal and durable aortic valve function. Failures in earlier series were most likely related to underestimation of concomitant cusp pathology (ie, prolapse). The combination of root and cusp repair–guided by effective height as a cusp configuration parameter—allows for durable valve preservation in most patients. The addition of an annuloplasty improves aortic valve function further; however, long-term results for tricuspid valves are still pending. Current evidence indicates that individuals with connective tissue disease may be better treated by valve reimplantation. This may change in the future if new evidence is found.

FUNDING SOURCES
The authors have no funding sources to disclose.

DISCLOSURES
The authors have no conflicts of interest to disclose.

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