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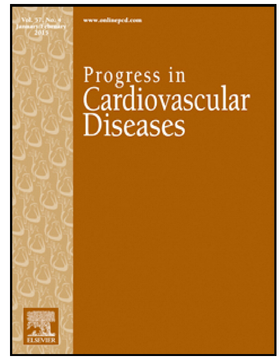

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State-of-the Art Bicuspid Aortic Valve Repair in 2020

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Alphabetical list of abbreviations:

AR= aortic regurgitation
AVR=Aortic valve replacement
BAV=bicuspid aortic valve

Abstract

Patients with a bicuspid aortic valve (BAV) frequently require surgical intervention for aortic regurgitation (AR) and/or aneurysm. Valve-preserving surgery and repair of regurgitant BAVs have evolved into an increasingly used alternative to replacement. Anatomic predictors of possible repair failures have been identified and solutions developed.

Using current techniques most non-calcified BAVs can be preserved or repaired. Excellent repair durability and freedom from valve-related complications can be achieved if all pathologic components of aortic valve and root including annular dilatation are corrected. Anatomic variations must be addressed using tailored approaches.

Introduction

The bicuspid aortic valve (BAV) is the most common congenital cardiac anomaly with an incidence of 0.5-2% (1, 2). It has 2 functional commissures of normal height, making it a bicommissural valve. A third, rudimentary commissure with variable height is almost always present. There is a variable degree of congenital fusion between the 2 cusps adjacent to the rudimentary commissure.

In BAVs, significant aortic stenosis develops at the age of 50-60 years, while aortic regurgitation (AR) develops usually at a younger age (3, 4). The BAV involves a spectrum of changes in the development of the heart and the aorta (5, 6), and aortopathy is an important part. Roughly 50% of individuals develop an aneurysm during their lifetime and may require surgery to avert the fate of aortic complications.

Repair techniques for AR and BAV-related aneurysm have evolved markedly over the past 2 decades. Excellent short-term results of repair were obtained initially, but a relevant incidence of repair failures was observed at mid-term follow-up (7-9). Over the years, several predictors and mechanisms of failure were identified. They were specifically addressed at the time of surgery, thus markedly improving repair durability. In addition, techniques have been developed and applied to treat patients with root aneurysm and non-calcified BAVs.

This review summarizes the general development and highlights current principles and outcomes of BAV repair.

Anatomy and Pathophysiology of BAV

The different fusion patterns in BAV cusps are right-left, right-noncoronary, and left-noncoronary. Right-left fusion is the most common, while fusion of the left and noncoronary cusp is rare (10-12).

The variability in commissural orientation (11, 12) is less frequently appreciated, although it has been shown to have a strong effect on repair durability (13). The orientation of the 2 functional commissures may vary from 180° (i.e. a symmetric configuration) to 120-140° (an almost tricuspid configuration) (11, 12). Finally, there is also variability in the degree of fusion, which seems to relate to commissural orientation (12). Symmetric commissures correlate with complete fusion, while the more asymmetric the commissural orientation, the less fusion is present (at times only 5 to 8 mm). In those instances, the rudimentary commissure may be of almost normal height (Fig. 1).

There are various classifications of BAV, with the classification proposed by Sievers most widely adopted (10). This classification is of limited utility in the context of BAV repair. Type 1 encompasses all circumferential orientations of a BAV, and type 2 is not a BAV, but rather a unicuspid aortic valve with different pathophysiology, natural history, requiring a completely different repair approach than a BAV. A different classification has recently been proposed (Fig. 1) which rests on the commissural orientation of the BAV (12). Commissural orientation has been observed to have a strong influence on repair durability (13) and also the choice of the most appropriate repair technique (12).

The mechanism of AR has common components in all phenotypes. Prolapse of the fused cusp is almost always present in regurgitant valves (7-9, 12-14). Cusp restriction, commonly seen in the area of the raphe and usually in asymmetric or very asymmetric valves, may similarly lead to insufficiency. In the very asymmetric BAVs with an almost tricuspid-like appearance (120-140° orientation), prolapse may primarily be present in the rudimentary right cusp. In a limited, but relevant proportion of cases, the non-fused cusp may also exhibit prolapse, possibly as a result of long-standing regurgitation. Annular dilatation is almost always observed in regurgitant BAVs (15), and its presence impacts repair durability if left uncorrected (13, 16-18).

Annular dilatation and the resulting need for annular stabilization have also increased the importance of the detailed annular anatomy. The true anatomic annulus is best represented by the crown-shaped fibrous structure of the cusp insertion lines (19). On the other hand, the caudal border of the root, which connects the cusp nadirs along a horizontal plane (also known as the basal ring) should probably be considered as the functional annulus because it determines valve geometry (20). This basal plane can differ from the aortoventricular junction, with the aortoventricular junction lying more cranial, i.e. distal than the virtual basal ring (19). In normal tricuspid aortic valves, this difference is generally limited (20, 21). In BAVs, however, a more pronounced distance between basal plane and aortoventricular junction (reaching up to 10-15mm in height) may be encountered (12), particularly in the right sinus. This is morphologically characterized by a “paper thin” sinus wall, thus an anatomic phenomenon rather than a sign of aortic degeneration.

Finally, aortic dilatation is often present in patients with BAVs and can be a contributing factor to the pathophysiology of AR. Progressive dilatation of the aortic root after BAV repair can result in recurrence of AR during follow-up. It is important to recognize and address these anatomic details at the time of surgery.

BAV-Related Aortopathy

BAV is associated with dilatation of the proximal aorta, independent of valvular dysfunction, in approximately 50% of patients. Previously, aortic dilatation in the presence of a BAV was considered to be associated with a disproportional increased risk of acute aortic events akin to Marfan's syndrome, and guidelines suggested earlier intervention compared to a tricuspid aortic valve (22). Clinical history studies have challenged this paradigm, demonstrating that although the BAV aortic dissection risk is higher than the general population, it remains low in absolute terms (23, 24).

The BAV associated aortopathy has been classified into different categories based on the location of dilatation (25, 26). The most common variant consists of ascending aortic dilatation with varying degrees of root dilatation. The isolated root phenotype is uncommon, but is mainly observed in younger patients with AR. For practical purposes, it is reasonable to distinguish between aortopathy of the root type and the tubular type. At this time it is still uncertain whether the presence of tubular aortic dilatation indicates an increased probability of secondary enlargement of the aortic root (27).

Why Repair?

Aortic valve replacement (AVR) with mechanical or biologic prostheses has long been the procedure of choice. Although prosthetic AVR is effective in correcting the hemodynamic problem, there are important long-term drawbacks. These are particularly present in a younger patient population, such as the majority of individuals with a BAV. Mechanical prostheses are more durable than biologic valves, but reoperation rates are in the range of 0.5 to 1% per patient year. More importantly, survival in non-elderly adults following elective isolated mechanical AVR is significantly lower than the age- and gender-matched general population (28, 29), with a mortality rate of ~1% per year (28-30). In addition, the need for lifelong anticoagulation has a direct impact on patient quality of life (31, 32) and is associated with significant risks of major hemorrhagic or thromboembolic events (33, 34).

Patients receiving biologic substitutes are at risk of structural valve degeneration, thromboembolism, patient-prosthesis mismatch and reoperation. Excess long-term mortality versus the matched general population in non-elderly adults has also been observed after biologic AVR (29, 35, 36); this appears to be aggravated in patients with patient-prosthesis mismatch (36). Despite current enthusiasm for biologic prostheses with subsequent valve-in-valve solutions, studies demonstrate better long-term outcomes with mechanical versus biological prostheses (30, 37).

In recent years, there has been renewed interest for the Ross procedure in adults. Several studies have shown long-term survival equivalent to the age- and sexmatched general population, excellent hemodynamics, and low rates of valve-related complications (38, 39). However, aside from the technical complexity of the Ross procedure, the risk of reoperation remains a concern, especially in patients presenting with AR. Interestingly, when performed in centers of expertise using tailored techniques, the risk of Ross reintervention in patients with AR is only 1%-1.5% per patient-year range with excellent survival (40). Nonetheless, the Ross operation remains a more complex procedure with potential for reintervention on two valves.

Over the past 20 years, BAV repair has become a seemingly better alternative to conventional AVR with favourable hemodynamics and survival (41-44). The incidence of valve-related complications is low (45-47), with repair failure being the most frequent of such complications. The probability of reoperation (most frequently due to recurrent AR) in different series has depended on the type of procedure and anatomic characteristics of the valve (13). Nevertheless, with careful patient selection and adequate repair and valve-preserving techniques, durability of >20 years has been documented (48).

Importantly, BAV repair and the Ross procedure should not be seen as competing techniques, but rather as complimentary; both aim at preserving a living valve in the aortic position. If the aortic valve can be preserved or repaired, the Ross procedure is a future option in the event of repair failure. In contrast, if the valve can not be repaired and in the presence of appropriate expertise, the Ross procedure currently provides the best perspective for survival and quality of life (31, 32, 38-40).

History of BAV Repair

Initial series of BAV repair were reported in the early 90's by Cosgrove and coworkers (7, 8) mainly consisting of free margin plication or triangular resection of the fused prolapsing cusp tissue. Subcommissural plication was added as suggested by Cabrol (49) to increase the area of leaflet coaptation. Early results were promising; however intermediate results revealed freedom from reoperation of only 87% at 5 years (9). Repair failure was mainly due to recurrent AR (9). Proposed risk factors of failure were triangular resection and dilatation of the ascending aorta (9, 50). It has subsequently been confirmed that the ascending aorta in BAV patients can continue to dilate even after AVR (50, 51). Therefore, a liberal use of aortic replacement in order to stabilize an aortic repair was proposed (52).

Determinants of BAV Repair Durability

Cusp Size and Configuration

A later analysis of repair failures revealed that symmetric prolapse, i.e. of both cusps was one of the mechanisms of repair failure (53). This prolapse could either go by undetected or underestimated at the time of surgery; it could also be induced through surgical correction of aortic dilatation, thus reducing intercommissural distance. The realization led to the concept of effective height, i. e. the distance between the central free margin and the annluar plane in diastole (fig. 2a, 54). Normal effective height in healthy control subjects was determined to range from 9 to 10 mm (55). A caliper was developed for objective assessment of cusp effective height intraoperatively (fig. 2b, 54). Thus, cusp configuration could be measured precisely for guidance for detection and correction of prolapse. Effective height can also be determined by intraoperative echocardiography, thus providing morphologic information before or after repair (fig. 2c). This approach to assessing valve configuration has been used by others, systematically aiming for an effective height of ≥9mm, and this has improved early and long-term valve function (13, 55-57).

It also became clearer that the ability to correct aortic valve function is related to the amount of cusp tissue present. A simple measurement was introduced ("geometric height") of the distance from the nadir of the cusp to the central free margin (fig. 2a, 58). In BAVs, the geometric height of the nonfused cusp was found to be ≥20 mm (mean 24 mm) in 95% of individuals (58). This cut-off value can be used as a surrogate parameter for the detection of cusp retraction. Using geometric height for selection of adequate repair substrate, and measurement of effective height to guide correction of prolapse, repair has become more reproducible and results more predictable.

Annular Dilatation

The importance of annular dilatation on repair durability was recognized in several studies (13, 17, 18). Annular dilatation (>25-27mm) is present in the majority of patients with severe AR, and is even more pronounced in patients with a BAV. Annular dilatation was found to be an independent risk factor for recurrence of regurgitation, at least in isolated BAV repair (13, 17)**.** Stabilizing and/or reducing the aortic annulus at the time of surgery has been shown to significantly improve the durability of BAV repair (16-18). Even though the sinotubular junction contributes to valve form – similar to the basal ring – it is as yet unclear how much the stabilization of both structures (59) improves long-term valve durability.

Commissural Orientation

The relevance of commissural orientation was recognized also through the analysis of failures (13). The best durability (10) and flow characteristics across the aortic root (60) were seen with a commissural angle of 160° to 180°. Applying standard repair techniques in BAVs with a commissural angle of <160° resulted in higher systolic gradients and poor durability (61)**.** The introduction of systematic modification of commissural orientation has been shown to likewise markedly improve systolic valve function and repair durability (61). As an alternative, liberal root replacement for moderately dilated sinuses has been proposed in order to facilitate repositioning of the commissures at or close to 180° (17, 48, 62).

Pericardial Patch Reconstruction

Pericardium has been employed for augmentation of retracted cusps, closure of perforations, or cusp reconstruction after excision of calcium (48, 63, 64). Several studies, however, have consistently shown that the use of pericardium as partial cusp replacement or augmentation was an independent risk factor for early failure (13, 48, 63, 64). The results have been particularly disappointing in the presence of BAV anatomy (63). Therefore, whenever patch reconstruction is required for BAV repair, this should be balanced against durability concerns.

Current Concepts of BAV Repair

Cusp Repair

Cusp repair is invariably required in isolated BAV repair for AR since pathology of the fused cusp – in most instances prolapse - is a key component; cusp retraction is less frequent. In addition, there may also be prolapse or retraction of the non-fused cusp. Correction of cusp prolapse will also frequently be necessary in valve-preserving aortic surgery, since the reduction of intercommissural distance will frequently result in excess length of the cusp free margin (53).

Before actually starting cusp repair, a detailed assessment of cusp morphology, fusion pattern, circumferential orientation of the commissures, and presence of other pathology is important to determine the best repair strategy. Stay sutures are best placed in the commissures and kept under tension to provide adequate exposure and mimic a pressurized aortic root (65). Annular dimensions – which have been measured by transesophageal echocardiography - are re-assessed by direct intubation, such as a Hegar dilator. The limited orifice opening of the valve implies that smaller Hegar dilators are used and the excess diameter estimated. The valve is inspected visually (eye-balling), geometric height and effective height of the non-fused cusp (reference cusp) can be measured with a ruler and caliper (54, 58, 65) for more objective assessment.

Selection of adequate substrates for repair is an important part of the procedure. The cusp tissue should be pliable and without calcification, there should be an adequate amount of cusp tissue. This is best determined by measuring geometric height in the non-fused cusp (fig. 2d); a geometric height of ≥20mm will be sufficient for repair (58). The diagnosis of retraction on the fused cusp relies more on visual assessment. Probably a minimal geometric height of 15 mm on the 2 components of the fused cusp is sufficient for repair.

In order to facilitate assessment of cusp configuration and identify prolapse reproducibly, intraoperative measurement of effective height with a caliper is useful (54). In BAVs the level of aortic insertion of the fused cusp varies. Therefore, effective height can only be reliably measured in the non-fused cusp. The nonfused is then used as reference for the fused cusp; because of the variability of height of aortic insertion and other geometric characteristics determination of effective height is not reproducible on the fused cusp. An effective height of 9-10 mm of the nonfused cusp with symmetry of both margins has consistently led to stable results unless other complicating pathology was present.

Induced prolapse due to reduction of intercommissural distance is a frequent finding if associated aortopathy is treated by aortic replacement involving the sinotubular junction. In such cases, it is important to perform or repeat cusp assessment after aortic replacement when intercommissural distance has been reduced to its final level.

Central plication of the cusp free margin has proven to be the most reproducible technique for correcting cusp prolapse in the past 20 years (13, 56, 65-67). This portion of the cusp is non-load bearing, which improves stability of this approach (68, 69). The plication is primarily done at the level of the free margin (fig. 3) and –

depending on the extent of prolapse and excess geometric height – may be extended into the belly of the cusp to limit potential billowing of the cusp. Since prolapse of the fused cusp is essentially always present, the plication will be applied to this cusp regularly. If there is additional prolapse of the non-fused cusp, both cusps can be corrected without negatively impacting the results.

A “figure-of-eight” suture in the pericommissural area has been proposed (70) to correct prolapse. Although this may be effective intra-operatively, durability of this repair is a relevant concern. Sutures placed in the pericommissural areas of the cusp can tear out more easily because this portion of the root is under highest stress (68, 69, 71). Weaving a thin expanded polytetrafluorethylene suture has been proposed as an alternative technique. The main challenge with this technique is that the extent of cusp free margin reduction is more difficult to judge compared to plication, and it is easy to overcorrect when tying.

Not infrequently, dense fibrosis or even calcification may be present in the raphe. Excision of excess fibrotic tissue from the raphe may improve the mobility of the fused cusp and also increase the geometric height of the fused cusp in its central portion. If central plication is difficult because of excess calcification along the fusion line, a triangular resection of the calcified tissue is a valid alternative (65). Most sugeons prefer interrupted polyethylene sutures (e.g. 5-0) to re-approximate the cusp tissue; a continuous over-and-over suture may lead to cusp retraction. Some used a continuous locked suture (72). If cusp calcification extends beyond the fusion line or along the surface of the cusps, insertion of a patch would be necessary in order to avoid restriction. Under such circumstances BAV repair should be reconsidered because of limited durability.

Root Configuration

Commissural orientation is an important part of BAV anatomy and must be taken into consideration when choosing the repair strategy. A commissural angle of 160°-180° can be left as it is. If the angle is 140°-160°, its modification has shown to decrease postoperative systolic gradients and improve mobility of the fused cusp and durability (61, 62, 73). This can be achieved by plication of the fused sinus (fig. 5), starting at the base and reaching into the level of the sinotubular junction (61).

Alternatively it may be performed through root replacement and change of the configuration inside a graft for reimplantation (62) or also through appropriate configuration of the graft tongues in root remodeling (48, 65). If the commissural angle is <140°, the valve is probably best treated in analogy to tricuspid aortic valves if the rudimentary commissure is sufficiently high. In this setting, prolapse of individual cusps is treated separately.

Concomitant Aortic Replacement

Classically, absolute aortic dimensions are used as determinants of concomitant aortic replacement (22). Current guidelines recommend surgical intervention in patients with ascending aortic diameter of >55 mm in patients with a BAV, >50 mm if risk factors are present, and >45 mm if the aortic valve triggers the need for surgery

(22). These recommendations, however, do not differentiate between valve repair and replacement. Indeed, if the valve is repaired, concomitant aortic replacement (in mildly dilated aortas) has been associated with improved durability (13, 17, 62).

In deciding for root replacement the surgeon should take into consideration the increased complexity of the procedure and weigh it against the improved durability of repair after root replacement. Whenever root dimensions are enlarged (> 42 to 43 mm), ascending aorta and root are replaced in many dedicated repair centers in the context of valvular repair. The graft size must accommodate the size of the patient as well as the size of the cusps. For both forms of root replacement, reimplantation and remodeling, the commissural orientation of the graft is optimally placed at 180° (62, 65). It is important to ensure that the commissures are placed high during root replacement to avoid commissural restriction. The longest follow up exists with root remodeling (48). Recent data have indicated similar results for remodeling and reimplantation up to 10 years (74-76). More data are necessary to determine the fate of these procedures in the second and third postoperative decade.

If root dimensions are preserved (depending on age and body surface area of the patient), most surgeons refrain from replacing the root. Mid- to long-term observations have shown stability of the aortic root with such an approach if a circular annuloplasty was used (13, 16). Recently, more liberal root replacement has been proposed to treat annular dilatation (62). The advantage of this approach over isolated cusp repair and concomitant annuloplasty in improving repair durability is yet unproven.

Aortic Annuloplasty

Annular dilatation is an independent predictor of AR progression in BAV (15). Therefore, annular dilatation is almost always present in insufficient BAVs and has been shown to lead to poor repair durability (13). In the absence of better data, a common definition of annular dilatation mandating an annuloplasty is a diameter ≥ 25-27mm. Previously, subcommissural plication sutures have been used for correction of annular dilatation (13, 17, 49, 67). It was found, however, that subcommissural plication did not stabilize the annulus sufficiently (17) and were actually associated with repair failure (13). This technique has therefore been abandoned by most surgeons.

Of the techniques currently used, mainly 4 different forms of annuloplasty exist (62, 76-78).

In applying the annuloplasty the anatomic characteristics of the aortic annulus in the BAV must be considered. For repair, the virtual basal ring (19) connecting the nadirs of the sinuses is much more important than the true anatomic annulus. In BAVs, a pronounced distance (reaching up to 10-15mm in height) between basal plane and aortoventricular junction may be encountered (12), particularly along the right coronary sinus. This implies that for external placement of an annuloplasty device relatively deep dissection into the myocardium is necessary to place the device at the basal level. Outside the right sinus this external root dissection is similar to that of harvesting a pulmonary autograft.

Therefore some surgeons favour a suture annuloplasty using expanded polytetrafluorethylene (fig. 5a; PTFE; CV-0, Gore-Tex CV-0; WL Gore and

Associates, Munich, Germany), which has proven to be a good material for this purpose (16). The suture is placed circumferentially at the level of the basal ring and tied around a Hegar dilator at the desired annular diameter, both in isolated repair or as adjunct to root remodeling.

Alternatively, an external ring may be used for extra-aortic annuloplasty in cases of root remodeling (55, 74-76). When performing isolated BAV repair, a band (instead of a ring) can be placed in sub-coronary fashion (fig. 5b) and closed at the nadir of the non-coronary sinus (59, 79). Regardless of any external annuloplasty technique, careful attention to the specific anatomy of the left coronary artery is critical to avoid interference with the left main or the circumflex coronary. The addition of a supplemental ring at the level of the STJ to increase the durability of isolated BAV repair may occasionally be considered. An advantage of such a STJ ring (Fig 5b) was reported in a series with limited stratification for known predictors of failure (59); this needs to be confirmed in larger series with longer follow-up.

Valve reimplantation has also been proposed as an annuloplasty technique with good mid-term results (62). Since this is an external stabilization, the surgical dissection is similar to placement of an external band.

Internal placement of a rigid annuloplasty device has been proposed which does not require external, deep dissection (78). So far, experience with that device is very limited and there are only mid-term data. Potential concerns are possible mechanical interference with cusp tissue leading to local trauma, and uncertainty regarding possible dehiscence of a device that aims to contain expansion of the left ventricular outflow tract from within.

The use of annuloplasty (with suture or ring) has markedly improved repair durability after isolated valve repair (16). The addition of annuloplasty to root remodeling in BAV has resulted in a higher proportion of completely competent aortic valves (48); an improvement in freedom from reoperation is less clear (48).

When Not to Repair?

Limitations of repair are primarily related to the morphology of the cusps and commissures. Currently, the need for cusp augmentation or partial replacement of cusps using patch material remains associated with poor durability (48, 63). This is due to degeneration of autologous pericardium currently used for cusp replacement; in some instances also progressive calcification of the whole valve has been observed in patients who required partial cusp replacement after calcium excision. Thus, cusp retraction (geometric height <20mm) or calcification of the raphe that cannot be treated by direct approximation of cusp tissue are scenarios that are currently better treated by replacement. The presence of active endocarditis seems to fall into a similar category (80).

Unfavorable commissural orientation will increase the complexity of the repair and decrease its durability (12, 13). Although asymmetric or very asymmetric BAVs can be repaired, they represent a higher technical challenge to the surgeon. Similarly, closure of fenestrations in BAVs and the creation of a tricuspid design by a commissural reconstruction are associated with decreased durability (63). In such scenarios the threshold for replacement should be low in light of potentially shorter durability. Keeping these considerations in mind, still 90% of BAVs have been repairable in a large series (81).

Results of Repair

Due to the evolution in selection of appropriate BAV pathology and tailored repair strategies, older reports will give an inadequate impression of the results of repair. Using current approaches for selection of repairable valves and also current repair strategies, isolated repair of a regurgitant BAV has been possible with 10-year freedom from reoperation of 90% (73, 82). In a limited cohort not specified for BAV, survival was superior to that seen after replacement (44). In an analysis focusing on BAV patients, survival has been similar to that of a gender- and age-matched population (82). Thus, results are superior to what has been published for conventional aortic replacement (28-30, 33-37).

Conclusion

The science and surgical techniques behind BAV repair have evolved significantly over the past 2 decades. Careful analysis of failure has identified BAVs that are likely not to be suitable substrates for repair. Techniques have become standardized and reproducible, thus offering a tailored and predictable approach for the majority of patients with regurgitant BAVs. Improved understanding of the mechanisms of BAV regurgitation, predictors of repair durability, and surgical techniques should translate into wider adoption of repair for most BAVs.

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References

1. Ward C. Clinical significance of the bicuspid aortic valve. Heart 2000;83(1):81-85.
2. Siu SC, Silversides CK. Bicuspid aortic valve disease. J Am Coll Cardiol 2010;55(25):2789-2800.
3. Masri A, Kalahasti V, Alkharabsheh S et al. Characteristics and long-term outcomes of contemporary patients with bicuspid aortic valves. J Thorac Cardiovasc Surg 2016;151(6):1650-1659 e1651.
4. Michelena HI, Desjardins VA, Avierinos JF et al. Natural history of asymptomatic patients with normally functioning or minimally dysfunctional bicuspid aortic valve in the community. Circulation 2008;117(21):2776-2784.
5. El-Hamamsy I, Yacoub MH. A measured approach to managing the aortic root in patients with bicuspid aortic valve disease. Curr Cardiol Rep 2009;11(2):94-100.
6. Della Corte A, Body SC, Booher AM et al. Surgical treatment of bicuspid aortic valve disease: Knowledge gaps and research perspectives. J Thorac Cardiovasc Surg 2014;147(6):1749-1757, 1757 e1741.
7. Cosgrove DM, Rosenkranz ER, Hendren WG, Bartlett JC, Stewart WJ. Valvuloplasty for aortic insufficiency. J Thorac Cardiovasc Surg. 1991 Oct;102(4):571-6; discussion 576-7.
8. Fraser CD, Jr., Wang N, Mee RB et al. Repair of insufficient bicuspid aortic valves. Ann Thorac Surg 1994;58(2):386-390.
9. Casselman FP, Gillinov AM, Akhrass R et al. Intermediate-term durability of bicuspid aortic valve repair for prolapsing leaflet. Eur J Cardiothorac Surg 1999;15(3):302-308.

10. Sievers HH, Schmidtke C. A classification system for the bicuspid aortic valve from 304 surgical specimens. J Thorac Cardiovasc Surg 2007;133(5):1226-1233.
11. Sabet HY, Edwards WD, Tazelaar HD et al. Congenitally bicuspid aortic valves: A surgical pathology study of 542 cases (1991 through 1996) and a literature review of 2,715 additional cases. Mayo Clin Proc 1999;74(1):14-26.
12. de Kerchove L, Mastrobuoni S, Froede L et al. Variability of repairable bicuspid aortic valve phenotypes: Towards an anatomical and repair-oriented classification. Eur J Cardiothorac Surg 2019.
13. Aicher D, Kunihara T, Abou Issa O et al. Valve configuration determines long-term results after repair of the bicuspid aortic valve. Circulation 2011;123(2):178-185.
14. Ridley CH, Vallabhajosyula P, Bavaria JE et al. The Sievers classification of the bicuspid aortic valve for the perioperative echocardiographer: The importance of valve phenotype for aortic valve repair in the era of the functional aortic annulus. J Cardiothorac Vasc Anesth 2016;30(4):1142-1151.
15. Yang LT, Pellikka PA, Enriquez-Sarano M, Maalouf JF, Scott CG, Michelena HI. Stage B Aortic Regurgitation in Bicuspid Aortic Valve: New Observations on Progression Rate and Predictors. JACC Cardiovasc Imaging. 2020 Mar 12.. [Epub ahead of print]
16. Schneider U, Hofmann C, Aicher D et al. Suture annuloplasty significantly improves the durability of bicuspid aortic valve repair. Ann Thorac Surg 2017;103(2):504-510.

17. Navarra E, El Khoury G, Glineur D et al. Effect of annulus dimension and annuloplasty on bicuspid aortic valve repair. Eur J Cardiothorac Surg. 2013 Aug;44(2):316-22; discussion 322-3.
18. Lansac E, Di Centa I, Sleilaty G, et al. Long-term results of external aortic ring annuloplasty for aortic valve repair. Eur J Cardio-thorac Surg 2016;50:350-60.
19. Loukas M, Bilinsky E, Bilinsky S, Blaak C, Tubbs RS, Anderson RH. The anatomy of the aortic root. Clin Anat. 2014 Jul;27(5):748-56.
20. de Kerchove L, Jashari R, Boodhwani M et al. Surgical anatomy of the aortic root: Implication for valve-sparing reimplantation and aortic valve annuloplasty. J Thorac Cardiovasc Surg 2015;149(2):425-433.
21. Khelil N, Sleilaty G, Palladino M et al. Surgical anatomy of the aortic annulus: Landmarks for external annuloplasty in aortic valve repair. Ann Thorac Surg 2015;99(4):1220-1226.
22. American College of Cardiology, et al. ACC/AHA 2006 guidelines for the management of patients with valvular heart disease: A report of the american college of cardiology/american heart association task force on practice guidelines. J Am Coll Cardiol 2006;48(3):e1-148.
23. Tzemos N, Therrien J, Yip J et al. Outcomes in adults with bicuspid aortic valves. JAMA 2008;300(11):1317-1325.
24. Michelena HI, Khanna AD, Mahoney D et al. Incidence of aortic complications in patients with bicuspid aortic valves. JAMA 2011;306(10):1104-1112.
25. Fazel SS, Mallidi HR, Lee RS et al. The aortopathy of bicuspid aortic valve disease has distinctive patterns and usually involves the transverse aortic arch. J Thorac Cardiovasc Surg 2008;135(4):901-907, 907 e901-902.

26. Della Corte A, Bancone C, Quarto C et al. Predictors of ascending aortic dilatation with bicuspid aortic valve: A wide spectrum of disease expression. Eur J Cardiothorac Surg 2007;31(3):397-404; discussion 404-395.
27. Park CB, Greason KL, Suri RM, Michelena HI, Schaff HV, Sundt TM 3rd. Fate of nonreplaced sinuses of Valsalva in bicuspid aortic valve disease. J Thorac Cardiovasc Surg. 2011 Aug;142(2):278-84.
28. Bouhout I, Stevens LM, Mazine A et al. Long-term outcomes after elective isolated mechanical aortic valve replacement in young adults. J Thorac Cardiovasc Surg 2014;148(4):1341-1346 e1341.
29. Kvidal P, Bergstrom R, Horte LG et al. Observed and relative survival after aortic valve replacement. J Am Coll Cardiol 2000;35(3):747-756.
30. Goldstone AB, Chiu P, Baiocchi M et al. Mechanical or biologic prostheses for aortic-valve and mitral-valve replacement. N Engl J Med 2017;377(19):1847-1857.
31. Aicher D, Holz A, Feldner S et al. Quality of life after aortic valve surgery: Replacement versus reconstruction. J Thorac Cardiovasc Surg 2011;142(2):e19-24.
32. Zacek P, Holubec T, Vobornik M. Quality of life after aortic valve repair is similar to Ross patients and superior to mechanical valve replacement: a cross-sectional study. BMC Cardiovasc Disord. 2016 Apr 2;16:63.
33. Hammermeister K, Sethi GK, Henderson WG. Outcomes 15 years after valve replacement with a mechanical versus a bioprosthetic valve: final report of the Veterans Affairs randomized trial. J Am Coll Cardiol. 2000 Oct;36(4):1152-8.
34. Puskas J, Gerdisch M, Nichols D et al. Reduced anticoagulation after mechanical aortic valve replacement: Interim results from the prospective

randomized on-x valve anticoagulation clinical trial randomized food and drug administration investigational device exemption trial. J Thorac Cardiovasc Surg 2014;147(4):1202-1210; discussion 1210-1201.

35. Forcillo J, El Hamamsy I, Stevens LM et al. The perimount valve in the aortic position: Twenty-year experience with patients under 60 years old. Ann Thorac Surg 2014;97(5):1526-1532.

36. Mihaljevic T, Nowicki ER, Rajeswaran J et al. Survival after valve replacement for aortic stenosis: Implications for decision making. J Thorac Cardiovasc Surg 2008;135(6):1270-1278; discussion 1278-1279.

37. Glaser N, Jackson V, Holzmann MJ et al. Aortic valve replacement with mechanical vs. Biological prostheses in patients aged 50-69 years. Eur Heart J 2016;37(34):2658-2667.

38. El-Hamamsy I, Eryigit Z, Stevens LM, Set al. Long-term outcomes after autograft versus homograft aortic root replacement in adults with aortic valve disease: a randomised controlled trial. Lancet. 2010 Aug 14;376(9740):524-31.

39. Mazine A, El-Hamamsy I, Verma S, et al. Ross Procedure in Adults for Cardiologists and Cardiac Surgeons: JACC State-of-the-Art Review. J Am Coll Cardiol. 2018 Dec 4;72(22):2761-2777.

40. Poh CL, Buratto E, Larobina M, et al. The Ross procedure in adults presenting with bicuspid aortic valve and pure aortic regurgitation: 85% freedom from reoperation at 20 years. Eur J Cardiothorac Surg. 2018 Sep 1;54(3):420-426.

41. Graeter TP, Kindermann M, Fries R, Langer F, Schäfers HJ. Comparison of aortic valve gradient during exercise after aortic valve reconstruction. Chest. 2000 Nov;118(5):1271-7.
42. Collins JD, Semaan E, Barker A et al. Comparison of hemodynamics after aortic root replacement using valve-sparing or bioprosthetic valved conduit. Ann Thorac Surg 2015;100(5):1556-1562.
43. Ashikhmina E, Sundt TM, 3rd, Dearani JA et al. Repair of the bicuspid aortic valve: A viable alternative to replacement with a bioprosthesis. J Thorac Cardiovasc Surg 2010;139(6):1395-1401.
44. de Meester C, Pasquet A, Gerber BL et al. Valve repair improves the outcome of surgery for chronic severe aortic regurgitation: A propensity score analysis. J Thorac Cardiovasc Surg 2014;148(5):1913-1920.
45. Aicher D, Fries R, Rodionycheva S et al. Aortic valve repair leads to a low incidence of valve-related complications. Eur J Cardiothorac Surg 2010;37(1):127-132.
46. Price J, De Kerchove L, Glineur D et al. Risk of valve-related events after aortic valve repair. Ann Thorac Surg 2013;95(2):606-612; discussion 613.
47. Arabkhani B, Mookhoek A, Di Centa I et al. Reported outcome after valve-sparing aortic root replacement for aortic root aneurysm: A systematic review and meta-analysis. Ann Thorac Surg 2015;100(3):1126-1131.
48. Schneider U, Feldner SK, Hofmann C et al. Two decades of experience with root remodeling and valve repair for bicuspid aortic valves. J Thorac Cardiovasc Surg 2017;153(4):S65-S71.
49. Cabrol C, Cabrol A, Guiraudon G et al. [treatment of aortic insufficiency by means of aortic annuloplasty]. Arch Mal Coeur Vaiss 1966;59(9):1305-1312.

50. Moidl R, Moritz A, Simon P, et al. Echocardiographic results after repair of incompetent bicuspid aortic valves. Ann Thorac Surg. 1995;60(3):669-72.
51. Yasuda H, Nakatani S, Stugaard M et al. Failure to prevent progressive dilation of ascending aorta by aortic valve replacement in patients with bicuspid aortic valve: Comparison with tricuspid aortic valve. Circulation 2003;108 Suppl 1:II291-294.
52. Schäfers HJ, Langer F, Aicher D et al. Remodeling of the aortic root and reconstruction of the bicuspid aortic valve. Ann Thorac Surg 2000;70(2):542-546.
53. Aicher D, Langer F, Kissinger A et al. Valve-sparing aortic root replacement in bicuspid aortic valves: A reasonable option? J Thorac Cardiovasc Surg 2004;128(5):662-668.
54. Schäfers HJ, Bierbach B, Aicher D. A new approach to the assessment of aortic cusp geometry. J Thorac Cardiovasc Surg 2006;132(2):436-438.
55. Bierbach BO, Aicher D, Issa OA et al. Aortic root and cusp configuration determine aortic valve function. Eur J Cardiothorac Surg 2010;38(4):400-406.
56. Lansac E, Di Centa I, Sleilaty G, et al. Remodeling root repair with an external aortic ring annuloplasty. J ThoracCardiovasc Surg. 2017 May;153(5):1033-1042.
57. Schäfers HJ, Aicher D, Langer F et al. Preservation of the bicuspid aortic valve. Ann Thorac Surg 2007;83(2):S740-745; discussion S785-790.
58. Schäfers HJ, Schmied W, Marom G et al. Cusp height in aortic valves. J Thorac Cardiovasc Surg 2013;146(2):269-274.

59. Zakkar M, Bruno VD, Zacek P, et al. Isolated aortic insufficiency valve repair with external ring annuloplasty: a standardized approach. Eur J Cardiothorac Surg. 2020 Feb 1;57(2):308-316.
60. Stephens EH, Hope TA, Kari FA, et al. Greater asymmetric wall shear stress in Sievers' type 1/LR compared with 0/LATbicuspid aortic valves after valve-sparing aortic root replacement. J ThoracCardiovasc Surg. 2015 Jul;150(1):59-68.
61. Schneider U, Schmied W, Aicher D et al. Sinus plication to improve valve configuration in bicuspid aortic valve repair-early results. Ann Thorac Surg 2017;103(2):580-585.
62. de Kerchove L, Boodhwani M, Glineur D et al. Valve sparing-root replacement with the reimplantation technique to increase the durability of bicuspid aortic valve repair. J Thorac Cardiovasc Surg 2011;142(6):1430-1438.
63. Karliova I, Schneider U, Ehrlich T, Schäfers HJ. Results of Pericardial Patches in Tricuspid and Bicuspid Aortic Cusp Repair. Ann Thorac Surg. 2019 Aug 28.
64. Mosala Nezhad Z, de Kerchove L, Hechadi J et al. Aortic valve repair with patch in non-rheumatic disease: Indication, techniques and durability. Eur J Cardiothorac Surg 2014;46(6):997-1005; discussion 1005.
65. Schneider U, Schäfers H-J. Repair of the bicuspid aortic valve. Op Techniques Thor and Cardiovasc Surg 2017;22:91-109.
66. Langer F, Graeter T, Nikoloudakis N et al. Valve-preserving aortic replacement: Does the additional repair of leaflet prolapse adversely affect the results? J Thorac Cardiovasc Surg 2001;122(2):270-277.

67. El Khoury G, Vanoverschelde JL, Glineur D et al. Repair of bicuspid aortic valves in patients with aortic regurgitation. Circulation 2006;114(1 Suppl):I610-616.
68. Marom G, Haj-Ali R, Raanani E et al. A fluid-structure interaction model of the aortic valve with coaptation and compliant aortic root. Med Biol Eng Comput 2012;50(2):173-182.
69. Lavon K, Halevi R, Marom G et al. Fluid-structure interaction models of bicuspid aortic valves: The effects of nonfused cusp angles. J Biomech Eng 2018;140(3).
70. Zeeshan A, Idrees JJ, Johnston DR et al. Durability of aortic valve cusp repair with and without annular support. Ann Thorac Surg 2018;105(3):739-748.
71. Labrosse MR, Beller CJ, Boodhwani M, Hudson C, Sohmer B. Subject-specific finite-element modeling of normal aortic valve biomechanics from 3D+t TEE images. Med Image Anal. 2015 Feb;20(1):162-72.
72. Boodhwani M, de Kerchove L, Glineur D, et al. Repair of regurgitant bicuspid aortic valves: a systematic approach. J Thorac Cardiovasc Surg. 2010 Aug;140(2):276-284.
73. Mastrobuoni S, de Kerchove L, Navarra E, et al. Long-term experience with valve-sparing reimplantation technique for the treatment of aortic aneurysm and aortic regurgitation. J Thorac Cardiovasc Surg. 2019 Jul;158(1):14-23.
74. Kayatta MO, Leshnower BG, McPherson L et al. Valve-sparing root replacement provides excellent midterm outcomes for bicuspid valve aortopathy. Ann Thorac Surg 2019;107(2):499-504.

75. Lenoir M, Maesen B, Stevens LM et al. Reimplantation versus remodelling with ring annuloplasty: Comparison of mid-term outcomes after valve-sparing aortic root replacement. Eur J Cardiothorac Surg 2018;54(1):48-54.
76. Lansac E, Di Centa I, Raoux F et al. An expansible aortic ring for a physiological approach to conservative aortic valve surgery. J Thorac Cardiovasc Surg 2009;138(3):718-724.
77. Schneider U, Aicher D, Miura Y et al. Suture annuloplasty in aortic valve repair. Ann Thorac Surg 2016;101(2):783-785.
78. Rankin JS, Mazzitelli D, Fischlein T et al. Geometric ring annuloplasty for aortic valve repair during aortic aneurysm surgery: Two-year clinical trial results. Innovations (Phila) 2018;13(4):248-253.
79. Basmadjian L, Basmadjian AJ, Stevens LM et al. Early results of extra-aortic annuloplasty ring implantation on aortic annular dimensions. J Thorac Cardiovasc Surg 2016;151(5):1280-1285 e1281.
80. Mayer K, Aicher D, Feldner S, Kunihara T, Schäfers HJ. Repair versus replacement of the aortic valve in active infective endocarditis. Eur J Cardiothorac Surg. 2012 Jul;42(1):122-7.
81. Miyahara S, Schneider U, Morgenthaler L et al. (Almost) All Nonstenotic Bicuspid Aortic Valves Should Be Preserved or Repaired. Semin Thorac Cardiovasc Surg. 2019 Apr 10. pii: S1043-0679(18)30378-2.
82. Schneider U, Hofmann C, Schöpe J, et al. Reconstruction of bicuspid aortic valves - Long-term results of a differentiated anatomic repair concept. JAMA Cardiology, in press.

Legends

Figure 1

Anatomic variations of bicuspid aortic valves. On one side of the spectrum is a symmetric valve with complete fusion, 180° orientation of the commissures, and a very low or non-existent rudimentary commissure. On the other side is an almost tricuspid-looking valve with limited fusion and a rudimentary commissure that is almost as high as the functional commissures.

Figure 2a:

Schematic drawing of the aortic valve. The cusp dimensions that are important for valve configuration are geometric height of the cusp (gH), i.e. the amount of tissue, and effective height (eH) as configuration parameter.

2b:

using a caliper inside the aortic root effective height (eH) can be measured intraoperatively.

2c:

Echocardiographic image of an aortic valve in diastole. Geometric height is determined by measuring the distance from aortic insertion to free margin (19 mm). Effective height is determined as the distance from the annular plane to the free cusp margin (10 mm).

2d:

geometric height can be measured intraoperatively as the longest distance from the nadir of the aortic insertion to the free margin with the cusp stretched using a ruler

Figure 3

Schematic drawing of central plication sutures that are applied to correct prolapse (i.e. redundancy) of the fused cusp. The sutures are best placed in the central portion of the cusp.

Figure 4

Schematic drawing of the completed repair with modification of commissural orientation. The prolapse of the fused cusp has been corrected by plication sutures. The circumference of fused sinus has been reduced through plication of the aortic wall, thus bringing the commissures into a more symmetric configuration.

Figure 5a

Schematic drawing of a suture annuloplasty placed at the basal level of the root, i.e. the functional annulus.

Figure 5b

Schematic drawing of an external annuloplasty using a band placed at basal level. A second band or ring has been placed at sinotubular level (58).

Figures

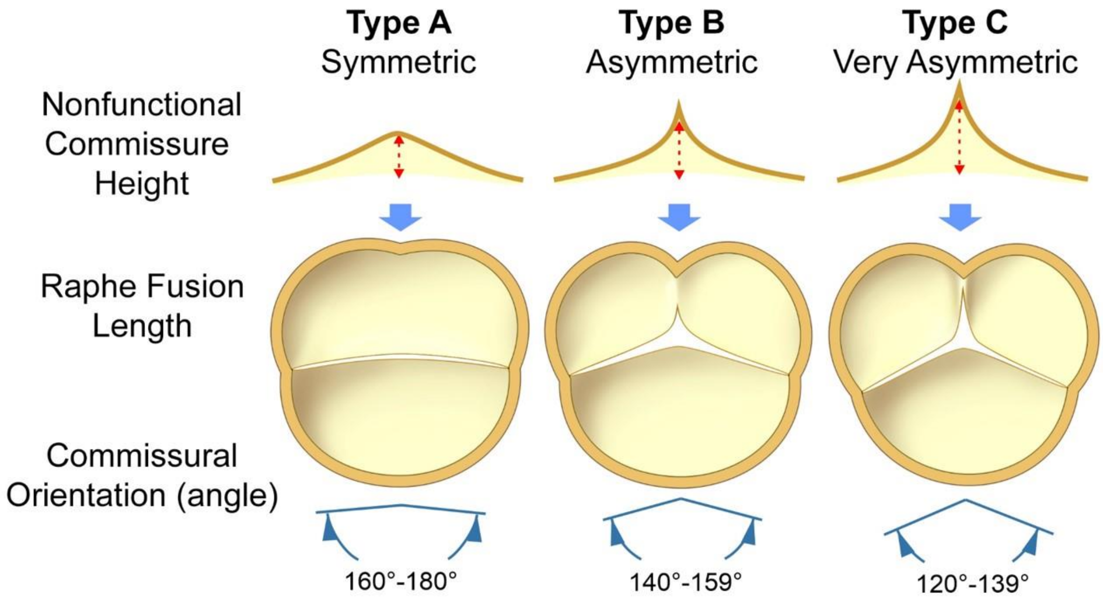


Figure 1

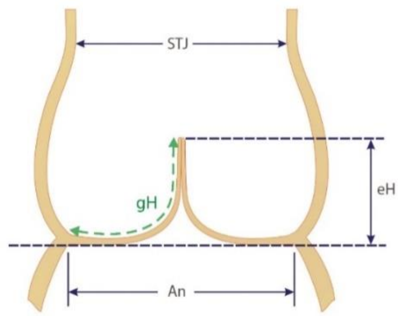
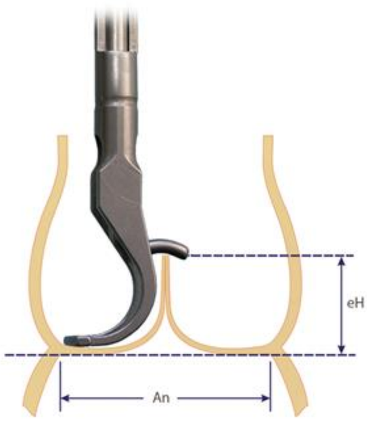


Figure 2a



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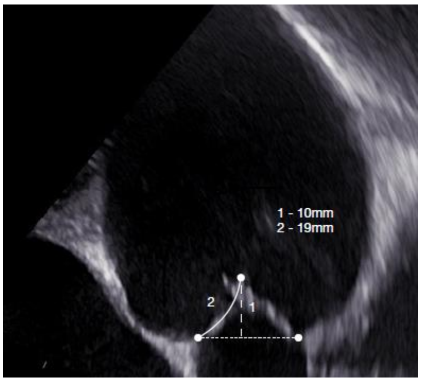

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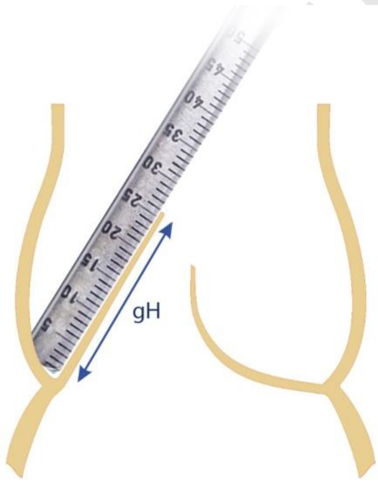

Figure 2d

Figure 3

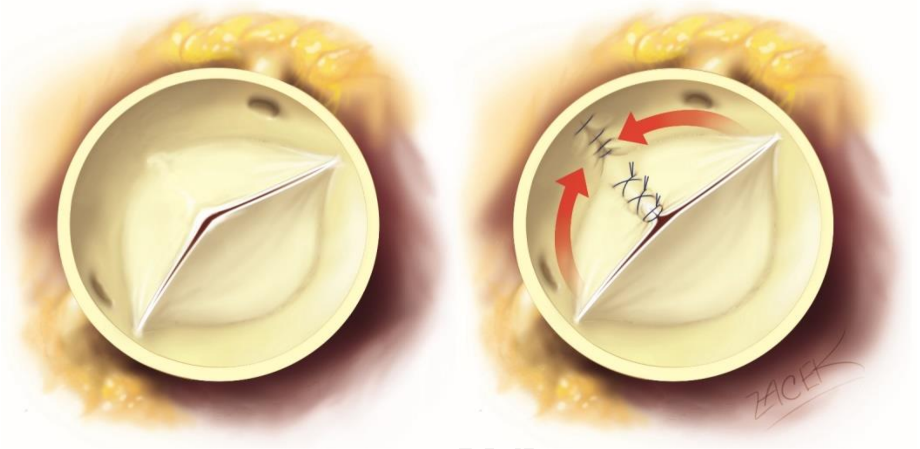

Figure 4

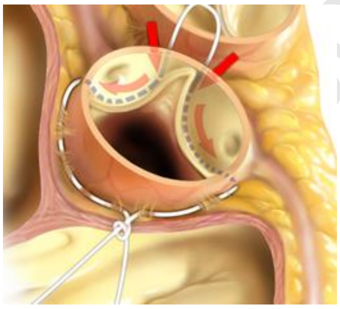

Figure 5a

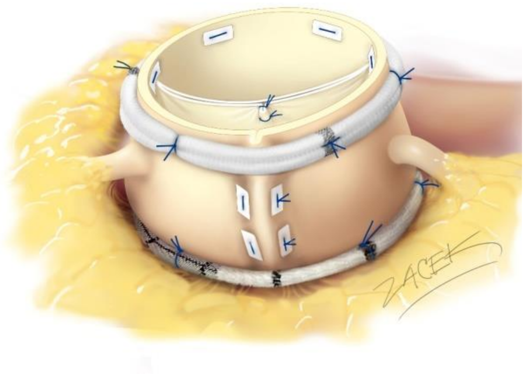

Figure 5b

Disclosures

HJS has a consultancy agreement with Cardiac Research and Education Saar GmbH.

RDP has received royalties from Terumo Aortic Inc. in relation to the design of a graft that reproduces the sinuses of Valsalva.

EL has consultant agreements with CORONEO, Inc in connection with the development of an aortic ring bearing the trade name ‘Extra-Aortic’.