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EDITORIAL

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Aortic valve repair techniques: state of the art

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INTRODUCTION

Aortic valve (AV) repair is now recognized as a good alternative to prosthetic valve replacement in selected patients suffering from aortic insufficiency (AI) or proximal aorta aneurysm. Several pioneering cohorts have achieved long- or very long-term outcomes, up to 20 years, with excellent stability of the repair [1–3]. Moreover, active ongoing research has led to several significant improvements in the surgical techniques, like better repair stabilization using circumferential annuloplasty and systematic assessment of valve configuration using the effective height concept. As they have accumulated experience, the main schools have standardized their approaches and techniques to enhance the reproducibility and dissemination of AV repair.

The 2017 European Association for Cardio-Thoracic Surgeons/European Society of Cardiology guidelines for heart valve disease recommend a 'Heart Team discussion' for selected patients 'with pliable, non-calcified tricuspid (TAV) or bicuspid' aortic valve (BAV) insufficiency 'in whom AV repair may be a feasible alternative to valve replacement' (Class IC indication) (Fig. 1) [4]. According to results from the Euro Heart Survey on Valvular Heart Disease [5], patients with tricuspid or bicuspid dystrophic AI, which represents the most common aetiology of AI in Western countries, account for approximately two-thirds of the AI cases. These patients are usually good candidates for AV repair.

TERMINOLOGY

To enhance the reader's understanding of this review, we have provided the following definitions of specific terms commonly used in AV repair surgery (Figs 2 and 3):

- Valve type is defined by the number of cusps, which is based on the number of functional commissures (ordered by incidence): (i) a tricuspid valve has 3 fully developed commissures; (ii) a BAV has 2 fully developed commissures and 0 or 1 raphe on the fused cusp, also classified as bicuspid Type 0 or Type I [6]. A fused cusp is named according to the type of fusion, for example, R-L represents the most common type of right-left fusion. (iii) A unicuspid aortic valve has 1 fully developed commissure and 2 raphes and is also classified as bicuspid Type II. (iv) A quadricuspid valve has 4 commissures, 1 of which is often underdeveloped.
- A raphe of the fused or conjoined cusp, also called a non-functional commissure (underdeveloped commissure with a hypoplastic interleaflet triangle), is the area of fusion between 2 abnormally developed aortic cusps. The raphe is characterized by a certain length of fusion between the 2 cusps and a certain height of insertion on the aortic root wall. The presence of 1 or 2 raphes, even if incomplete, make the valves anatomically bicuspid or unicuspid.
- Commissure orientation is defined as the angle formed by the lines joining the commissures to the central axis of the valve. The angle measured is the one on the non-fused cusp side. It varies between 120° (tricuspid configuration) and 180° (bicuspid symmetrical configuration).
- The aortic annulus, also called the aortoventricular junction or basal ring, is defined as the plane passing through the nadir of the aortic cusps that can be measured either using echocardiography to obtain the long axis view or by direct intubation intraoperatively.
- The effective height (eH) is the orthogonal distance from the annulus to the middle of the free margin of the cusp. The eH can be measured by echocardiography and intraoperatively with a dedicated caliper. The normal eH in the adult population is close to 9 mm (8–10) [7].
- The geometric height (gH), also called the cusp height, is defined as the distance between the cusp nadir and the middle of the free margin. Intraoperatively, the gH is measured with a straight ruler along the aortic side of the cusp by applying gentle traction on the free margin to straighten the cusp tissue along the ruler. In adults, the cusp is considered

Indications for surgery in (A) severe aortic regurgitation and (B) aortic root disease (irrespective of the severity of aortic regurgitation)

Indications for surgery	Class[a]	Level[b]
A. Severe aortic regurgitation		
Surgery is indicated in symptomatic patients.[57,58,66,67]	I	B
Surgery is indicated in asymptomatic patients with resting LVEF ≤50%.[57,58]	I	B
Surgery is indicated in patients undergoing CABG or surgery of the ascending aorta or of another valve.	I	C
Heart Team discussion is recommended in selected patients[c] in whom aortic valve repair may be a feasible alternative to valve replacement.	I	C
Surgery should be considered in asymptomatic patients with resting ejection fraction >50% with severe LV dilatation: LVEDD >70 mm or LVESD >50 mm (or LVESD >25 mm/m^2 BSA in patients with small body size).[58,66]	IIa	B
B. Aortic root or tubular ascending aortic aneurysm[d] (irrespective of the severity of aortic regurgitation)		
Aortic valve repair, using the reimplantation or remodelling with aortic annuloplasty technique, is recommended in young patients with aortic root dilation and tricuspid aortic valves, when performed by experienced surgeons.	I	C
Surgery is indicated in patients with Marfan syndrome who have aortic root disease with a maximal ascending aortic diameter ≥50 mm.	I	C
Surgery should be considered in patients who have aortic root disease with maximal ascending aortic diameter:	IIa	C
• ≥45 mm in the presence of Marfan syndrome and additional risk factors[e] or patients with a *TGFBR1* or *TGFBR2* mutation (including Loeys–Dietz syndrome).[f]	IIa	C
• ≥50 mm in the presence of a bicuspid valve with additional risk factors[e] or coarctation.	IIa	C
• ≥55 mm for all other patients.	IIa	C
When surgery is primarily indicated for the aortic valve, replacement of the aortic root or tubular ascending aorta should be considered when ≥45 mm, particularly in the presence of a bicuspid valve.[g]	IIa	C

Figure 1: Indications for surgery in (**A**) severe aortic regurgitation and (**B**) aortic root disease (irrespective of the severity of Aortic regurgitation) [4]. Reprinted from Falk *et al.* [4] with permission from the ESC.

retracted when the gH is 16 mm or less in TAVs and 19 mm or less in the bicuspid non-fused aortic cusp [8].

- The coaptation height (cH), also called the coaptation length (cL), is defined as the distance of cusp apposition in diastole. It can be measured echocardiographically on the long axis view of the AV. The normal range is 4–5 mm.
- The cusp free margin is the free border or edge of the aortic cusp, running from 1 commissure to another. It participates along its entire length in the coaptation of the valve.

AORTA PHENOTYPES AND CLASSIFICATION OF AORTIC INSUFFICIENCY

AI disease is usually associated with a certain degree of proximal aortic dilation. Dilatation that involves the annulus, the sinuses of Valsalva or the sinotubular junction (STJ) directly influences AV function by reducing the coaptation and favouring the development of cusp prolapse. Three different phenotypes of proximal aorta dilatation are generally described because they require different types of surgical repairs. The first phenotype is normal root and ascending aorta; the second is dilatation of the aortic root and the third is dilatation of the ascending aorta. The annulus and STJ dilatation can be associated with any of these aortic phenotypes as a combined mechanism of AI (Fig. 4).

AI is also classified into 3 types according to the mechanism inducing insufficiency (Fig. 4). Type 1 AI is caused by aorta dilatation [9]. In this type, the regurgitation jet is generally central and the aortic cusps are stretched within the enlarged aorta and therefore can present some degree of restricted motion (cusp tethering). Type 2 AI corresponds to aortic cusp prolapse. Prolapse can be due to an abnormal elongation of the free margin of the cusp or induced by surgical reduction of the diameter of the root, particularly the STJ. Free margins are frequently elongated in cases of aorta dilatation, which explains the high risk of inducing prolapse during a valve-sparing root replacement (VSRR) procedure. In this type of AI, the cusps exhibit excessive motion and the regurgitation jet is eccentric. Finally, Type 3 AI is characterized by cusp retraction and reduced motion due to fibrosis or the calcification process. Type 3 AI presents central or eccentric regurgitation. The different types of AI frequently coexist with each other.

In general, better durability of AV repair is observed in patients with Type 1 and 2 AI compared to those with Type 3. Currently, we would not recommend AV repair for a patient with a pure Type 3 AI mechanism except in selected paediatric or adolescent patients. However, we would still consider a Type 3 repair in patients in whom the retraction or calcification is limited to a valve where the main mechanism of AI is a Type 1 or 2 (i.e. BAV with a fibrous or calcified raphe). Other experts have proposed that one avoid AV repair when the gH is smaller than 16 mm in TAV or 19 mm in BAV because these dimensions represent significant cusp retraction [8]. Furthermore, indications for AV repair must be balanced with age, complexity of the lesion and left ventricular function. Moreover, in all instances, strict intraoperative criteria should be applied; one should only consider the repair satisfactory if one has achieved a residual AI ≤Grade I central (<3 mm at the origin of the jet).

VALVE-SPARING ROOT REPLACEMENT: REIMPLANTATION OR REMODELLING WITH AORTIC ANNULOPLASTY?

In 1983, Magdi Yacoub was the first to describe VSRR using the remodelling technique. Ten years later, Tyrone David described VSRR using the reimplantation technique. Quickly thereafter, it was shown that one achieved better preservation of aortic root dynamics and physiologic cusp motion with the remodelling technique than with reimplantation technique using a straight tube graft (the so-called David I technique). Effectively, the neosinuses created during the remodelling allowed the root to expand through the interleaflet triangles while the reimplantation constrained the root structure within the tube graft, which led to the risk that the cusp would be damaged by touching the graft in systole. On the other hand, several authors reported that a dilated annulus (>25–28 mm) was a risk factor for recurrence of AI after remodelling, which was not the case with the reimplantation

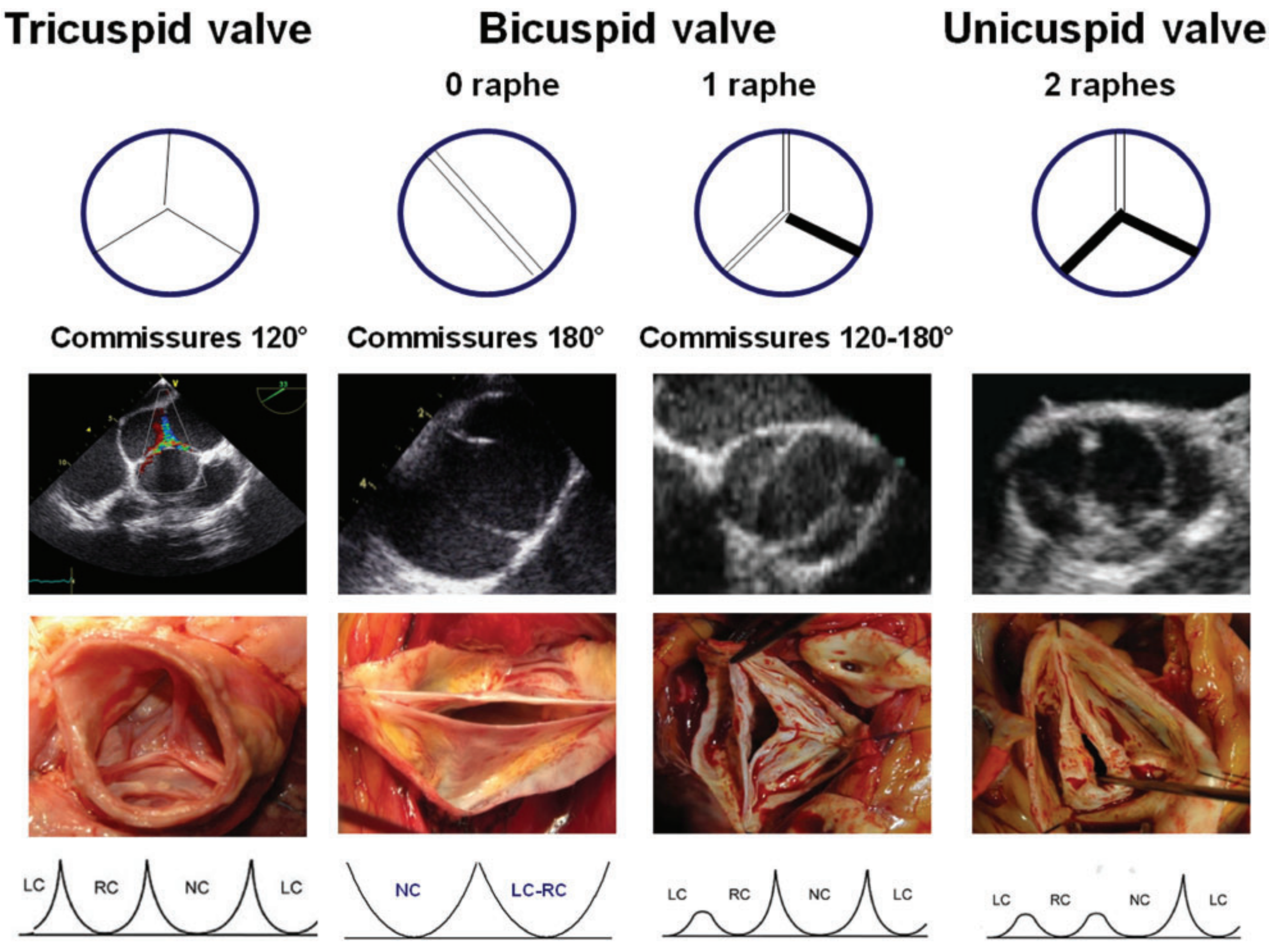

Figure 2: Valve type including commissural orientation and variation of aortic annulus morphology in relation to the leaflet insertion line. LC: left coronary; NC: non coronary; RC: right coronary.

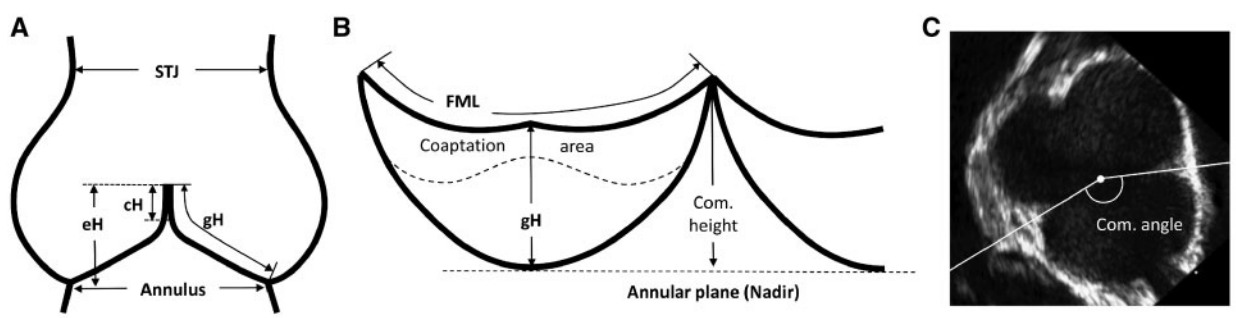

Figure 3: Diagram of aortic valve and root illustrating the different anatomical measurements used in aortic valve repair and described in this editorial. cH: coaptation height (**A**), Com. angle: commissure angle (**C**), Com. height: commissure height (**B**), eH: effective height (**A**), FML: free margin length (**B**), gH: geometric height (**A** and **B**), STJ: sinotubular junction diameter (**A**).

technique that includes an annuloplasty through the proximal suture of the tube [3, 10, 11]. The consequences of these different findings were that both techniques were adapted taking into account their respective weaknesses. Neosinuses were created using different techniques in the reimplantation procedure to improve blood flow and cusp motion within the graft, and a circumferential external annuloplasty was added to the remodelling technique [1–3, 12]. The effect of this annuloplasty was to restore the normal annulus diameter, which is frequently enlarged in patients with dystrophic root aortopathy (formerly called annuloaortic ectasia) (Fig. 5).

The technical modifications of the VSRR procedures were not the only reason they gained in reproducibility and durability. The introduction of the systematic intraoperative measure of eH permitted one to assess objectively the cusp geometry and to diagnose pre-existent or induced cusp prolapse during VSRR. In the case of cusp prolapse, the central cusp plication technique, by reducing the length of the free margin, allows the eH to be increased to approximately its normal value of 9 mm. Good alignment of all cusp free margins with the intraoperative eH measure has been shown to significantly improve the durability of the VSRR [3].

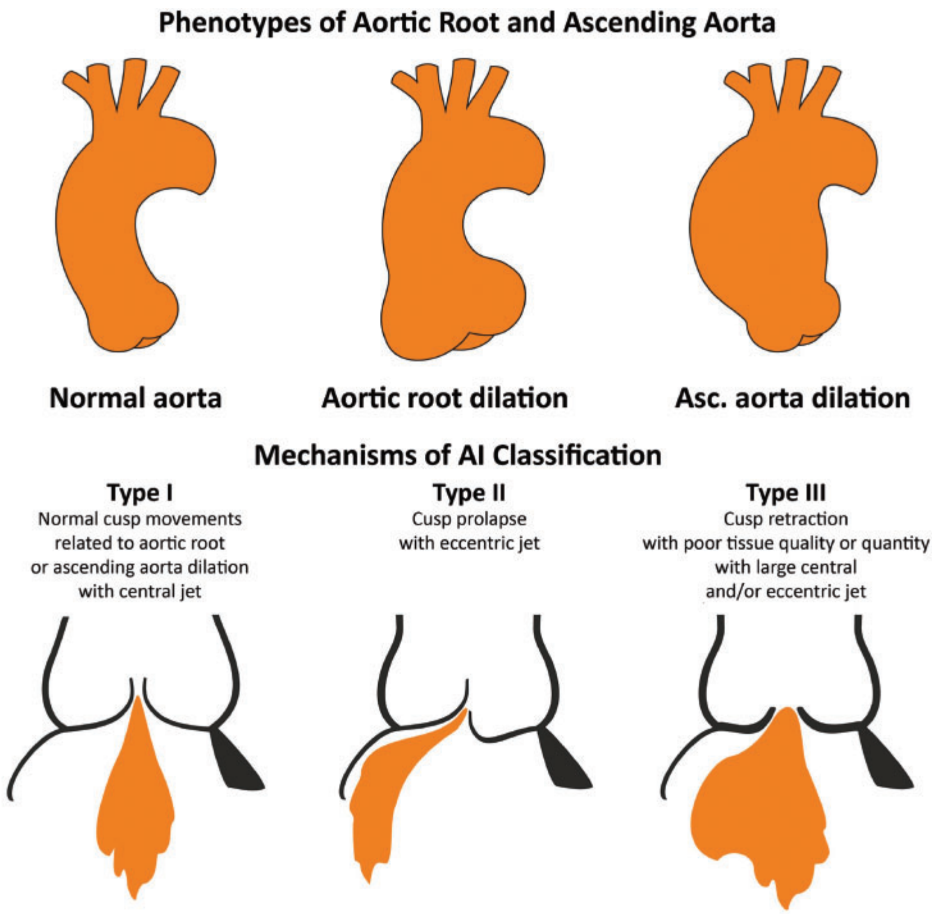

Figure 4: Phenotypes of the proximal aorta associated with the classification of aortic insufficiency mechanisms. Annulus and sinotubular junction dilatation can be associated with any aortic phenotypes as a combined mechanism of AI. AI: aortic insufficiency; Asc. Aorta: ascending aorta.

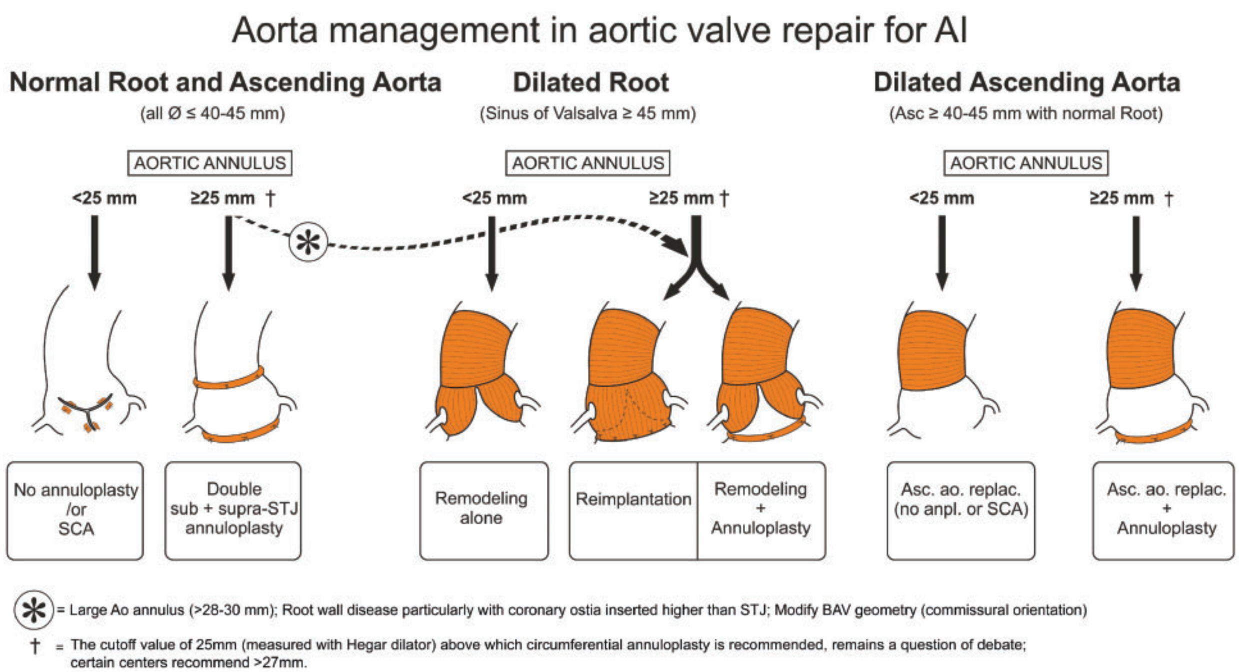

Figure 5: Algorithm of management of the aorta in aortic valve repair for aortic insufficiency. Drawing by Pavel Zacek (used with kind permission). AI: aortic insufficiency; Asc. ao. replac.: supracoronary ascending aorta replacement; annulus; BAV: bicuspid aortic valve; no anpl.: no annuloplasty; SCA: subcommissural annuloplasty; STJ: sinotubular junction.

Long-term data accumulated on VSRR techniques have shown that, in an experienced centre, freedom from reoperation can reach 96% after almost 20 years with the reimplantation technique used in the Tyrone David historical cohort [1]. The remodelling technique associated with the calibrated expansible aortic ring annuloplasty and systematic eH assessment was shown to improve valve repair outcomes with a freedom from valve-related reoperation at 7 years of 99.1% ± 0.9% [2]. Moreover, patients who have VSRR report an excellent quality of life and an extremely low rate of valve-related events [2]. In accordance with these excellent long-term results, since 2014, the guidelines recommend that one consider 'aortic valve repair, using the reimplantation or remodelling with aortic annuloplasty technique, in young patients with aortic root dilation and tricuspid aortic valves' (Class Ic indication) [4].

Actually, although more than 80% of aortic root aneurysm operations are undertaken for dystrophic AI with a tricuspid or bicuspid valve, a recent analysis of the Society of Thoracic Surgeons database revealed that only 14% of these patients had a VSRR procedure (20% in low-risk patients and 6% in high-risk patients) [13]. In fact, in most centres, VSRR surgery remains highly selective for young patients with TAV and with no or only limited central AI. Effectively, the cases with a low probability of needing cusp repair are the easiest to handle and have the best outcomes. However, it has been shown that remodelling with annuloplasty or reimplantation and systematic intraoperative cusp assessment yield also excellent repair durability in patients with severe, eccentric AI and in patients with BAV [1–3, 9, 12].

REPAIR OF ISOLATED AORTIC VALVE REGURGITATION

AV replacement in patients with isolated AI (no aorta dilatation) has been the gold standard for many years and is considered a safe, reproducible procedure. However, prosthetic valve replacement has significant limitations, especially in the young population, in whom it is associated with thromboembolism, bleeding, limited long-term durability and eventually reduced life expectancy compared to the general matched population. Even if AV repair versus replacement has never been prospectively randomized, recent data in the literature suggest that AV repair can offer prolonged durability compared to a bioprosthesis and a better survival rate and a better quality of life with fewer valve-related events compared to a mechanical valve.

As with any valve, the durability of the repair depends mainly on 2 factors: (i) the quality of the valvular tissues and (ii) the technique used to repair the valve. Cusp tissue quality is generally good in Type 1 and 2 AI and poor in Type 3. Cusp prolapse (Type 2 AI) is the main mechanism of valve dysfunction in isolated AI, and its repair follows the same rule as that described in VSRR. Cusp prolapse is defined as a free margin level that is lower than the adjacent one or an eH that is below the normal value. Prolapse repair includes a central plication stitch to shorten the free margin and to increase its level. Extension of the plication from the free margin towards the cusp belly for a few millimetres prevents the cusp from billowing. The goal is not only to bring up the prolapsing cusp to a normal eH but also to equalize the level of all free margins of the cusps. Overcorrection of the prolapse can occur; therefore, cusp mobility should always be checked after repair; the cusps must touch each other in the centre of the valve, and the eH should not be above the normal value. Free margin resuspension with a running suture of Gore-Tex 7/0 is an alternative technique to treat cusp prolapse; it can also be used to reinforce the free margin or to close a small fenestration. This technique is used less frequently because it may be associated with overcorrection or late stenosis in BAV.

Cusp fenestrations, also called commissural fenestrations, are a congenital variance comprising a gap with no cusp tissues in a small area of the cusp near the commissure and just below the free margin. Most fenestrations within the coaptation area do not induce AI; therefore, their presence does not contraindicate valve repair and does not necessitate any specific management during AV repair. However, in certain cases, fenestration can be involved in the cusp prolapse mechanism (i.e. by elongation or rupture of the free margin in relation to the fenestration). In those cases, the area of the fenestration should be closed and reinforced using a small pericardial patch. Several authors have advocated avoidance of AV repair or the sparing procedure in cases of multiple large fenestrations associated with extremely thin cusp tissues, as is observed in some patients with Marfan syndrome. This particular situation is under debate.

In addition to a ruptured fenestration, several other cusp lesions may need patch repair. In infective endocarditis, for example, when cusp destruction is limited, the valve can be repaired using a pericardial patch to close a perforation or to reconstruct part of 1 cusp. A unicuspid valve can be transformed into a symmetrical BAV using a patch to reconstruct a functional commissure or, with a similar technique, a severely asymmetrical BAV can be transformed into a true TAV. Finally, congenital valve stenosis or a rheumatic valve can be repaired in paediatric patients using a patch as a cusp extension. In general, patch repair is a factor that reduces repair durability and is driven by the structural degeneration of the patch material and by the progression of disease involving the native valve (i.e. rheumatic disease, BAV, unicuspid aortic valve). However, when a patch is used to repair a limited area of the valve in predominantly Type 1 or 2 AI disease (i.e. fenestration, endocarditis), one can still expect good long-term durability. In growing patients, AV repair, even with a patch, seems to be a good option because it allows the annulus to grow normally and it also allows the eventual Ross operation to be delayed to an advanced age where the pulmonary homograft is better tolerated. Although treated autologous and xenopericardium have shown similar rates of degeneration in AV repair, the focus is currently on biological matrix scaffolds (i.e. decellularized xenopericardium) that are under clinical investigation for AV repair.

In isolated AI, next to cusp disease, a certain degree of root dilatation, including the annulus and the STJ, is generally present even if the dimensions are below the criteria for replacement (sinus of Valsalva <40–45 mm). Therefore, it is important in those cases to re-establish an adequate ratio between cusp size and both the annulus and the STJ diameter in a way that is stable over time. Multiple annuloplasty techniques have been described. In the 1960s, Taylor described circumferential annuloplasty using silk sutures placed externally below the coronary artery on the beating heart. In 1966, Cabrol proposed addressing both the annulus and the STJ using supra- and subcommissural plication stiches. The Cabrol subcommissural annuloplasty technique quickly spread worldwide, mainly because the technique is fast and easy to perform. However, it was recently demonstrated that subcommissural annuloplasty stitches are not appropriate in a large annulus (>28–30 mm) because the annuloplasty effect disappears with time and is associated with a high risk of AI recurrence for bicuspid and tricuspid valves with a large annulus [9, 12]. In 2003, Lansac *et al.* developed double sub- and supravalvular annuloplasty techniques using 2 external rings placed at the annulus and STJ levels for isolated AV repair. This technique showed results comparable to those of the valve-sparing procedure with 97.4% freedom from reoperation at 7 years [14]. In a comparative analysis, better repair durability was shown with the double sub- and supravalvular annuloplasty groups compared to the single subvalvular annuloplasty [14]. In 2013, Schäfers *et al.* reintroduced the concept of circumferential suture annuloplasty using the polytetrafluoroethylene Gore-Tex 0 suture [11]. In a recent study on isolated BAV repair, they showed that suture annuloplasty improved the mid-term outcomes compared to no annuloplasty [11]. To summarize, isolated AI repair is best stabilized with circumferential subvalvular annuloplasty, and a low threshold (if not systematic) should be applied for supravalvular STJ annuloplasty or ascending aorta replacement to restore both sub- and supravalvular diameters (Fig. 4).

BICUSPID AORTIC VALVE REPAIR

BAV disease affects 1–2% of the population. Although BAV can occasionally be associated with normal lifelong valve function, its presence is associated with a risk of early valve degeneration and aortopathy leading either to AI or stenosis and aortic aneurysm formation during adulthood. Young adults, who generally present with predominant AI, tend to have a higher rate of aortic root dilatation. In contrast, older patients, who typically present with predominant aortic stenosis, tend to have a higher rate of ascending aorta dilatation. AV repair is an attractive alternative to replacement in young adults with regurgitant BAV. During the last 2 decades, increased knowledge about BAV disease and refinement of surgical techniques have led to improved standardisation and reproducibility of BAV repair [11, 14].

BAV phenotypes fall along a spectrum with the 'symmetrical' BAV with a commissure orientation of 180° at one extremity and 'very asymmetrical' BAV with a commissure orientation close to 120° at the other extremity. In symmetrical BAV, the sinuses of Valsalva and the aortic cusps are of nearly equal size; the conjoined cusp is generally nearly completely fused. In a study from the Homburg group, commissure orientation >160° was correlated with improved repair stability compared to commissural orientation <160°. This interesting finding reflects either the presence of a better tissue substrate or of better haemodynamics (better cusp mobility and less turbulence) in symmetrical BAV compared to asymmetrical BAV. In addition to cusp phenotypes, BAV also present with a systematically large annulus (mean diameter: 30–32 mm in regurgitant BAV vs 27–28 mm in regurgitant TAV vs 23–24 mm in normal TAV) and eventually dilatation of the aortic root or the ascending aorta.

Even if BAV repair techniques still vary among the centres with larger numbers of cases [11, 12, 14], over the years the approaches have progressively reached similar goals comprising (Fig. 6) the following: (i) restoring cusp configuration with central cusp plication, raphe closure and intraoperative measure of the eH; (ii) reduction and stabilisation of the aortic annulus with

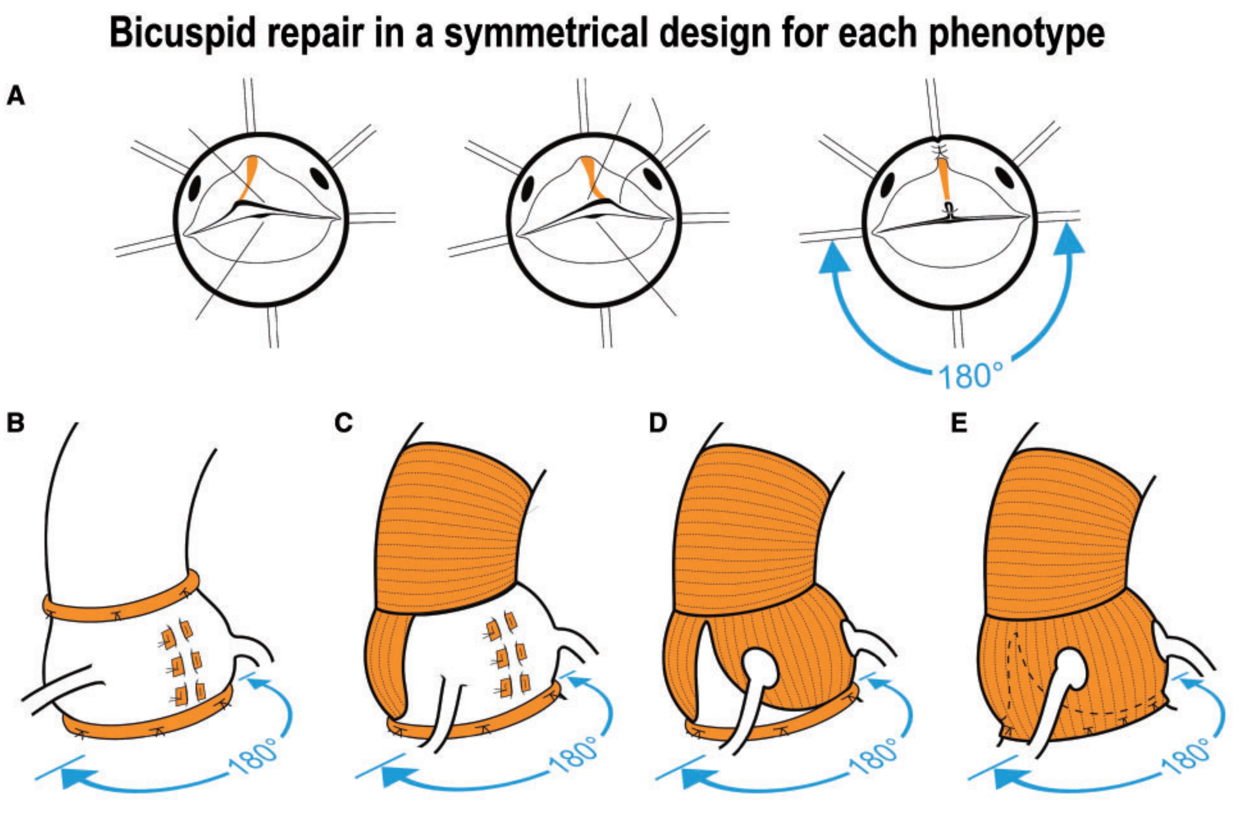

Figure 6: (**A**) Alignment of the cusp-free edge of the fused cusp along the length of the non-fused cusp; (**B**) isolated bicuspid repair with double annuloplasty, placing the commissure at 180° on the sinotubular junction ring in addition to external sinus plication at the level of the raphe; (**C**) hemi-remodelling by replacing the NC sinus and placing the commissure at 180° in addition to external sinus plication and subvalvular annuloplasty; (**D**) remodelling with 2 neosinuses, placing the commissure at 180° and subvalvular annuloplasty; (**E**) reimplantation, placing the commissure at 180°.

circumferential annuloplasty (i.e. external ring annuloplasty, suture annuloplasty or valve sparing reimplantation); (iii) valve-sparing root replacement using reimplantation or remodelling plus the annuloplasty technique when the root diameter is >45 mm. However, in the case of a bicuspid valve, a lower cut-off value for root replacement (40–45 mm) can be applied, in the presence of root wall disease, particularly when the coronary ostia are higher than the STJ, the annulus is large (>28–30 mm) and/or has an unfavourable commissural orientation (Fig. 4); (iv) improving valve geometry, making it more symmetrical (commissure orientation >160°) or leaving it at 120°. Both VSRR techniques allow reimplantation of the commissure at 180°. When the root size is normal, a sinus plication stitch on the side of the fused cusp, as described by Shäfers *et al.*, combined with a 180° placement of the commissure on an STJ ring, can increase the orientation of the commissure towards a more favourable valve geometry. Although the debate is still ongoing between an asymmetrical or a symmetrical design for AV repair, the main schools of thought currently favour the 180° or 120° orientation as the final commissure angle. Using such an approach for BAV repair, experienced centres were able to achieve excellent long-term durability with 90% or more freedom from reoperation after almost 1 decade [3, 11, 12, 14].

CONCLUSIONS

AV repair has reached a degree of maturity as evidenced in excellent long-term durability that is similar between TAV and BAV. These procedures, combined with the use of objective methods of cusp repair and a calibrated restoration of the aortic annulus/STJ ratio through either a VSRR (remodelling with annuloplasty or reimplantation) or an annuloplasty technique based on the proximal aorta phenotype, have been standardised. The fact that it is reproducible will allow AV repair eventually to become the new standard in selected young patients suffering from AI and/or aorta dilatation. As recently mentioned in a systematic review of a series of VSRRs, reports of valve-related events are unfortunately still very heterogeneous, emphasizing the need for uniform standardized reporting of AV repair procedures and their outcomes. Therefore, the AVIATOR Registry (supported by the Heart Valve Society) has been initiated to analyse large homogeneous cohorts of patients who will benefit from AV repair or replacement for AI or aortic aneurysm. The AVIATOR registry is open to any centre willing to participate (http://heartvalvesociety.org/AVIATOR/). The aim is to provide sufficient patient numbers to address key epidemiological and therapeutic issues and standardize indications for surgery as well as the place of repair versus replacement in AV surgery.

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Conflict of interest: Emmanuel Lansac has consultant agreements with the company CORONEO, Inc. (www.coroneo.com), in connection with the development of an aortic ring bearing the trade name 'Extra Aortic'. Emmanuel Lansac is the inventor of the aortic ring, whose patent rights have been assigned to the Assistance Publique Hôpitaux de Paris (APHP). The APHP has licensed the patent rights for this aortic ring to CORONEO under a Development and License Agreement.

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