Editorial: Cardiac Surgery

Aortic valve repair—"Pearls and Pitfalls"

Pouya Youssefi[1], Emmanuel Lansac[1], Pavel Zacek[2], Alain Berrebi[1], Daniel Czytrom[1], Leila Mankoubi[1], Milena Noghin[1], Christelle Diakov[1], Jean Luc Monin[1], Mathieu Debauchez[1]

[1]Department of Cardiac Surgery, Institut Mutualiste Montsouris, Paris, France; [2]Department of Cardiac Surgery, Hradec Kralove, Czech Republic

Correspondence to: Emmanuel Lansac, MD, PhD. Department of Cardiac Surgery, Institut Mutualiste Montsouris, Paris, France.

Email: emmanuel.lansac@imm.fr.

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Introduction

Current medical evidence shows that aortic valve repair reduces valve-related mortality with a better quality of life compared to prosthetic valve replacement. As a result, the 2017 European Association for Cardio-Thoracic Surgeons (EACTS)/European Society of Cardiology (ESC) guidelines for heart valve disease recommend to spare the valve in patients 'with pliable, non-calcified' bicuspid or tricuspid aortic valve insufficiency 'in whom aortic valve repair may be a feasible alternative to valve replacement' (class IC indication). They also recommend reimplantation or remodeling with aortic annuloplasty for valve-sparing root replacement, referring to the need of addressing the annulus (1). Indeed a dilated aortic annulus ≥25 mm, if left untreated, is clearly documented as a major risk factor for failure of bicuspid and tricuspid aortic valve repair procedures (2,3). As in the case of mitral valve repair, annuloplasty is now considered as an essential component of aortic valve (AV) repair/sparing procedures, aiming at a sustained long-term outcome by reducing the dilated aortic annulus and protecting the repair by improving the surface of coaptation. This review describes the anatomy behind aortic annuloplasty, the different historical techniques, as well as a standardised approach to aortic valve repair with ring annuloplasty according to each aorta phenotype.

Phenotypes of dystrophic aortic insufficiency (AI)

Dystrophic AI represents the most common aetiology of AI in western countries, accounting for approximately two-thirds of all cases (50% degenerative, 15% congenital) (4) which are good candidates for aortic valve repair. Dystrophic AI is characterized by dilatation of the aortic annulus, sinuses and/or sinotubular junction diameters. When either of these 2 anatomical rings are dilated, the surface of coaptation is reduced, and prolapse of cusp leaflets may be induced. Three phenotypes of AI can be described, depending on whether the sinuses of Valsalva and/or the tubular ascending aorta are dilated: (I) normal root and ascending aorta (all diameters <40–45 mm)—isolated AI; (II) dilatation of the aortic root (sinus of Valsalva ≥45 mm)—root aneurysm; (III) dilatation of the ascending aorta (≥45 mm)—tubular aorta aneurysm (*Figure 1*) (4).

Depending on cusp mobility, there are three types of valve dysfunction: type I characterized by normal cusp motion, associated with root/ascending aorta dilatation (central jet); type II defined as cusp prolapse (eccentric jet); and type III characterized by cusp retraction, associated with poor tissue quality and or quantity (central or eccentric jet). Type I and II are good candidates for repair of bicuspid and tricuspid aortic valves irrespective of the phenotype whereas type III is a more challenging entity for repair and needs to be considered on a case by case basis.

Although patients with dystrophic AI are good candidates for repair, only 1.7% of AI patients have their valve spared. The Society of Thoracic Surgeons' database analysis showed a slight improvement with 14% of patients who underwent aortic root surgery receiving a valve sparing procedure (20% of low risk and 6% of high risk patients), but still leaving 80% of root procedures for AI and/or root aneurysm as composite valve and graft replacement (Bentall procedure) (5,6). Standardisation of aortic valve repair techniques which address the dilated diameters (sub and supra valvular annuloplasty) for each phenotype as well as cusp resuspension will be key for the dissemination of repair and long-term patient outcomes (*Figure 2*).

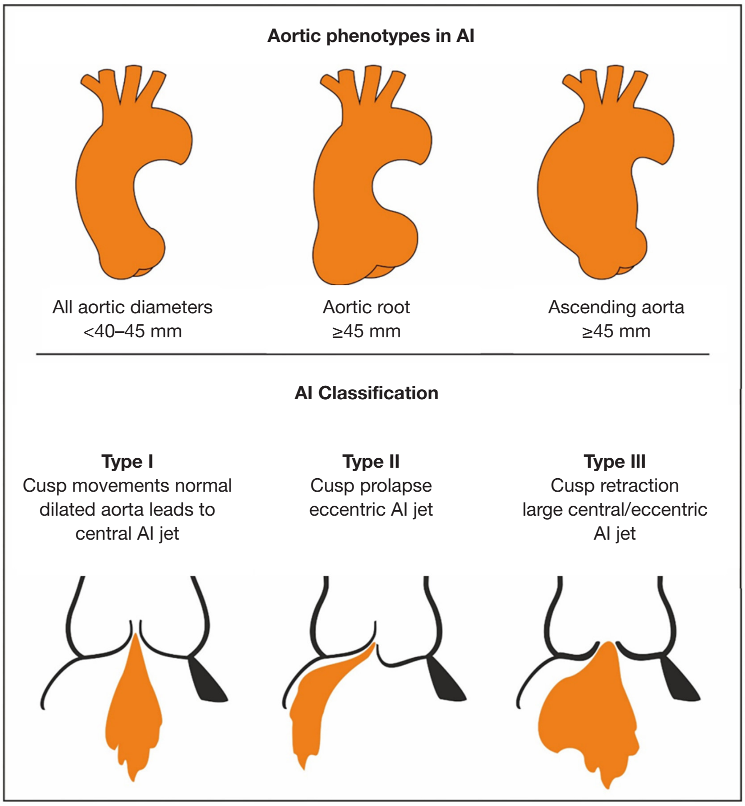


Figure 1 Phenotypes of the proximal aorta associated with the classification of AI mechanisms. Annulus and sinotubular junction dilatation can be associated with any aortic phenotypes as a combined mechanism of AI. AI, aortic insufficiency; Asc. Aorta, ascending aorta. Drawing by Pavel Zacek (used with kind permission).

Anatomical landmarks for aortic annuloplasty

The aortic valve is a dynamic complex with a systolic expansibility of the aortic root (6.2% and 5.7% at the aortic annulus and STJ levels respectively) allowing stress-free opening and closure of the cusps (7,8).

Large echocardiographic studies have documented that the sinotubular junction (STJ) [mean 27.2 mm (range, 24.7–29.5)] is larger than the aortic annulus [mean 22.3 mm (range, 20.5–24.5)] with a STJ/aortic annular base ratio of 1.2 (8,9). Therefore, an aortic annulus diameter larger than 25 mm and a STJ diameter larger than 30 mm are deemed as functionally dilated. Indeed finite element analysis has shown that the reduction of STJ induces a symmetrical prolapse by lowering the effective height (eH) of the cusp while dilation of aortic annulus diameter reduces mostly the coaptation height (cH) (10).

The aortic annulus is a consensus terminology to define the inflow of the aortic root as the plane passing through the nadir of the aortic cusps that can be measured either on echo long axis view or by direct intubation intra operatively (11-16). External dissection of the annulus may be achieved down to the subvalvular level below the nadir of the left and the non-coronary cusps (basal ring), and in 80% of cases below or within 3 mm of the nadir of the right cusp (11,17-21). Of importance to the surgical technique of dissecting down to the subvalvular level, it is difficult to fully reach down to the subvalvular plane in the region below the right-non commissure corresponding to the insertion of the membranous septum, right atrium wall, infundibulum and septal leaflet of the tricuspid valve. Therefore by dissecting down to this deepest plane, the external annuloplasty ring or the proximal suture line of the reimplantation tube graft would fully match the subvalvular plane below at least the left and non-coronary cusps, and remain below or within 3mm of the nadir of the right coronary cusp 80% of the time (*Figure 3*). The muscular part of the annulus is its thickest portion (with a mean thickness of 2.5 mm). Therefore, an external annuloplasty or proximal suture of

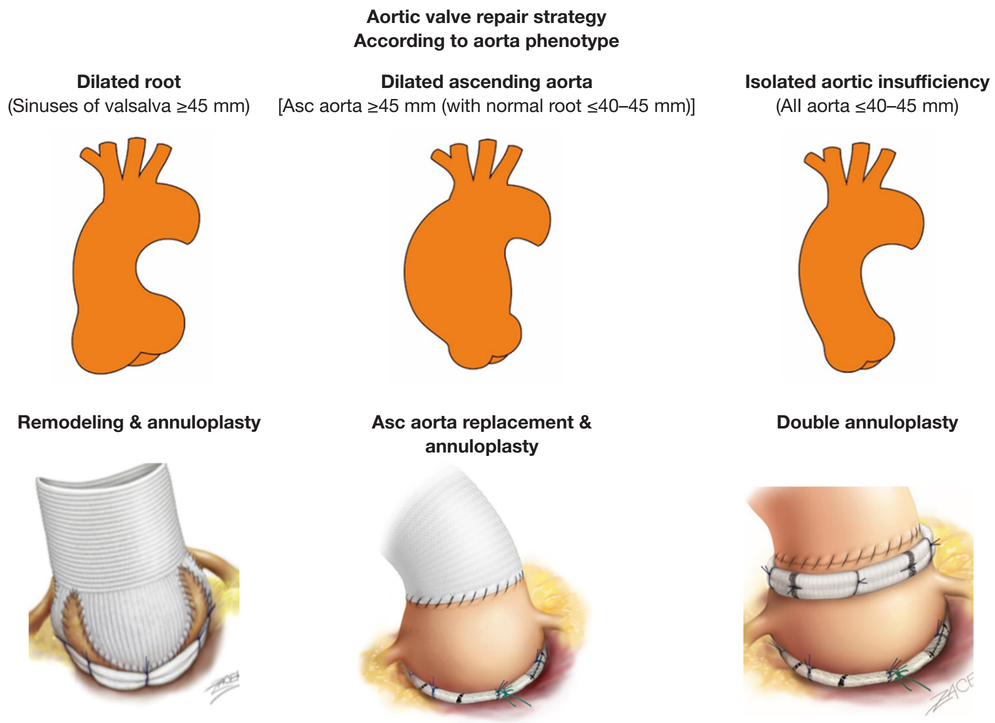


Figure 2 Algorithm of management of the aorta in aortic valve repair for AI. Drawing by Pavel Zacek (used with kind permission).

a reimplantation would produce a reduction in the annulus of at least 5 mm smaller than the size of the ring or graft (12,22).

Repairing the root—valve-sparing aortic root replacement

Replacement of the aortic root with preservation of the aortic valve has followed predominantly 2 different operations. The remodeling technique uses the tube graft to create 3 scallops or neo-sinuses to replace those of the native aorta. This technique allows root expansion during systole because the interleaflet triangles are not restricted by being placed inside the tube graft (23). The reimplantation technique requires the aortic valve to be placed within a tube graft (24). In both techniques the sinotubular junction is reduced by bringing the commissure to the diameter of the tube. Whereas the remodeling technique preserves the dynamic anatomy of the aortic valve (25), it does not on its own address the annulus. One of the risk factors for recurrent AI and re-operation after the remodeling technique is a dilated annulus (>25 mm) which has been left untreated. This is the case for both bicuspid and tricuspid valves (2,3,26,27). Modification of the remodeling technique to add an external expansile annuloplasty ring has led to significant improvements. In patients with a dilated aortic annulus, the external ring restores the normal annulus diameter and prevents future dilatation (26-31). On the contrary the reimplantation technique does provide an annuloplasty with the proximal suture line. However this

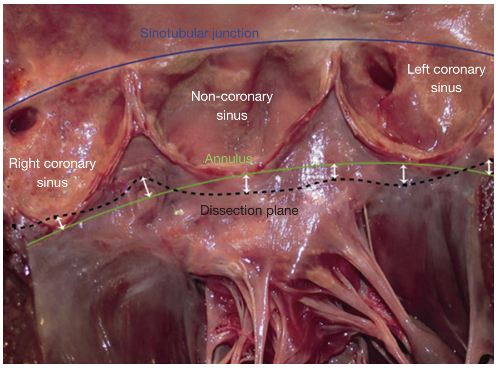


Figure 3 The aortic root opened with the cusps removed. The blue line indicates the sinotubular junction. The green line indicates the aortic annulus. The dotted line shows the subvalvular dissection plane.

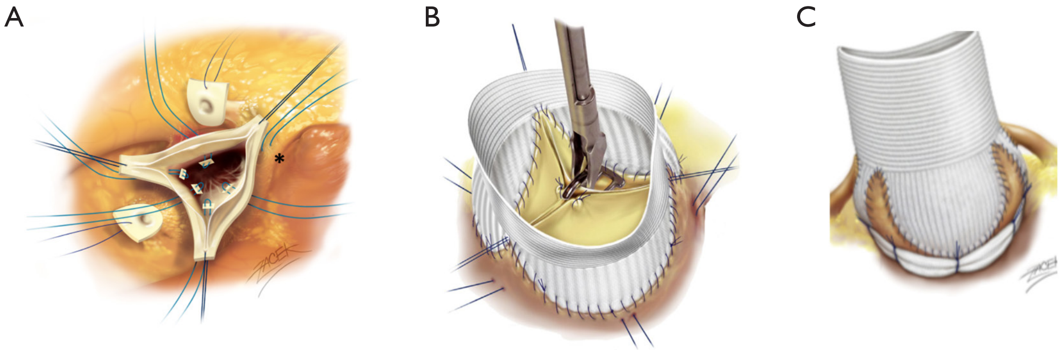


Figure 4 Standardized steps in remodeling of the aortic root associated with cusp effective height resuspension and external expansible subvalvular (Extra_Aortic, Coroneo Inc., QC, Canada) aortic ring annuloplasty. (A) Five "U" stitches are circumferentially placed, inside out, in the subvalvular plane except at the level of the commissure between the noncoronary and right coronary sinuses where a sixth stitch is placed externally to avoid damage to the membranous septum (*). Remodeling of the aortic root is then performed by scalloping a bulged graft. (B) Measure of cusp effective height with the caliper. (C) The anchoring "U" stitches are passed around the prosthetic aortic ring and tied down externally in the subvalvular position.

technique has inferior haemodynamics to the remodeling technique as there is loss of vortical flow, risk of cusp impaction on the tube graft and rapid valve closure (25). The original reimplantation technique (David I) has also been improved to incorporate a spherical bulb-shaped graft. This has been shown to improve cusp motion and vortical flow in the new root (32,33).

Apart from providing better valve dynamics, the choice of using remodeling + ring relates to both the standardization and reproducibility of valve repair. Whereas in the reimplantation technique the surgeon has to make a judgment on how high to place the commissures and in what circumferential orientation inside the graft, the commissures will follow the graft in the remodeling technique and will therefore be placed at the same level symmetrically. Furthermore, whereas the annuloplasty is the first step carried out in the reimplantation technique through the proximal suture line, it is the last step of the technique in remodeling + ring. Therefore, cusp effective height (see below) is measured in an untouched (often large) annulus, making accurate measurement easier (34-36). Finally, the fallback option in case of valve repair failure, contrary to the reimplantation proximal suture line, the external ring can simply be cut and removed, allowing large prosthetic valve implantation (*Figure 4*, *Table 1*).

There have been improvements in the long-term outcomes after valve-sparing root procedures. As well as addressing the annulus, this has been in part due to development of surgical techniques to address and repair the aortic valve cusps. Thus, aortic root repair no longer needs to be restricted to patients with insignificant AI. Even the severest forms of AI can be repaired due to advances in cusp management. The systematic measurement of cusp effective height (eH) has allowed the surgeon to assess for cusp prolapse, which may be pre-existing or induced as a result of the valve-sparing root procedure (2,37). The durability of valve-sparing root procedures has been significantly improved by ensuring an intra-operative eH of at least 9mm, and good alignment of cusp free margin length (2).

Isolated aortic valve repair

Isolated dystrophic AI is described when the sinuses of Valsalva and the ascending aorta are both ≤40–45 mm. Despite the aortic diameters being normal, isolated AI is still associated with an enlarged annulus ≥25 mm and/or STJ ≥30 mm in the majority of cases. This signifies the importance of addressing the annulus in all phenotypes of AI.

A number of different techniques of addressing the aortic annulus have been performed over the past 60 years (38). The first attempt was in 1958 when "aortic circumclusion" was performed to treat isolated AI by Taylor *et al*. Silk sutures were placed externally as a circumferential annuloplasty running underneath the coronary arteries on a beating heart (39) (*Figure 5*). In 1966, Cabrol performed the first internal annuloplasty using sub- and supra-commissural plication sutures of the interleaflet triangle (41,42). This was an attempt at dealing with both the annulus and

Table 1 Sizing algorithm for the calibrated annuloplasty ring (Extra_Aortic, Coroneo Inc, QC, Canada) and remodelling graft (Valsalva graft, Vascutek Ltd, Glasgow, UK) based on Hegar dilator measurement of aortic annulus size

	Aortic annulus diameter (Hegar dilator)			
	25–27 mm	28–30 mm	31–35 mm	≥36 mm
Valsalva graft (mm)	26	28	30	32
Extra aortic ring (mm)	25	27	29	31

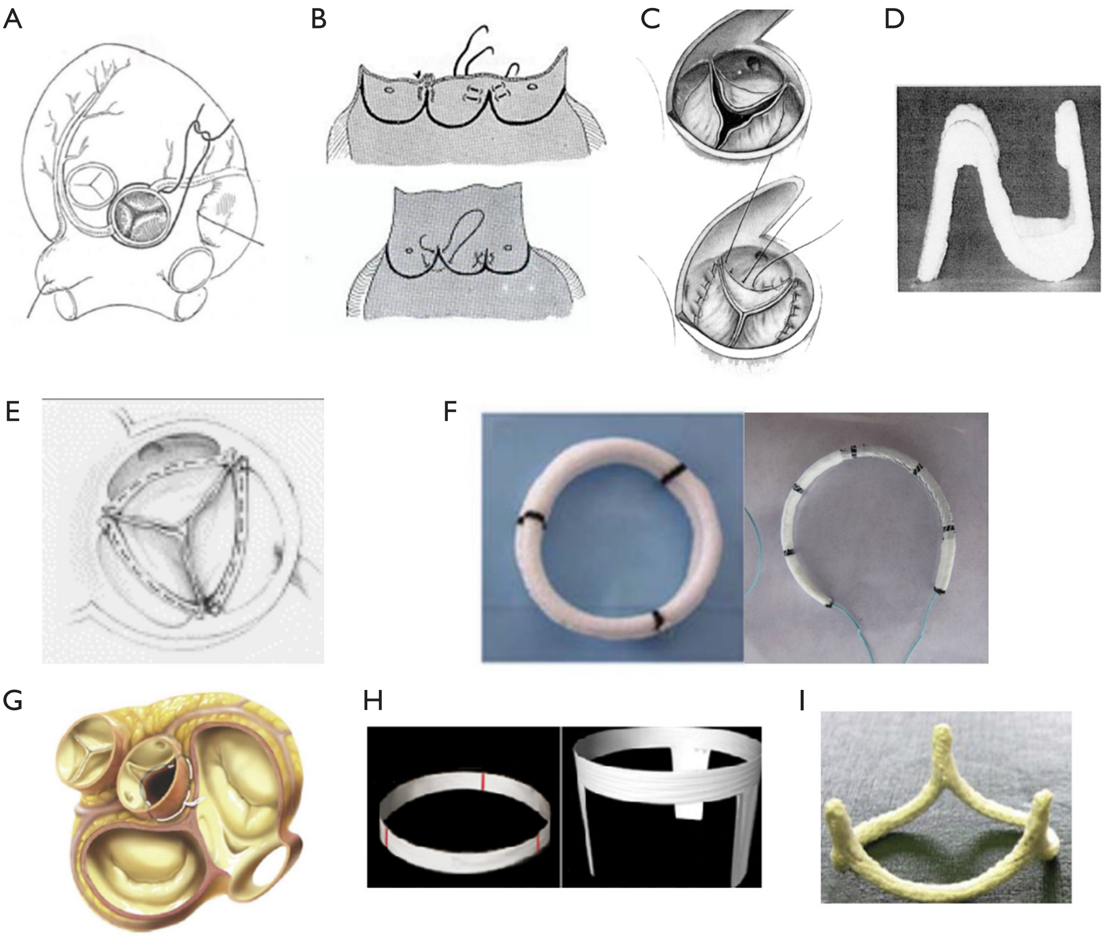
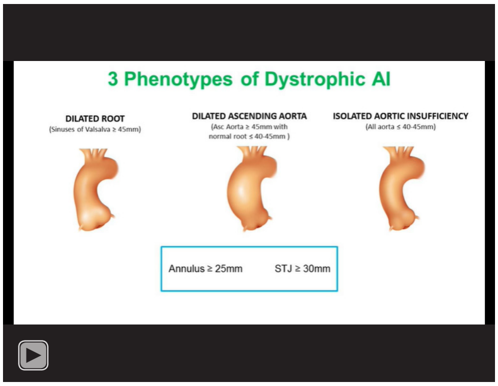


Figure 5 Different external annuloplasty techniques by Taylor 1958 (A), Cabrol 1966 (B), Carpentier 1983 (C), Duran 1993 (D), Haydar 1997 (E), Lansac 2003 (Coroneo, Inc. Extra-Aortic Ring) (F), Schafers 2009 (Suture Annuloplasty) (G), Fattouch 2011 (H), Rankin 2011 (HAART Ring) (I). Reprinted by permission from Springer Nature, Gen Thorac Cardiovasc Surg. Annular management during aortic valve repair: a systematic review. Form Kunihara *et al.* (in 2015) (40).

the STJ. However, high rates of recurrent AI have been reported with redilatation of the aortic annulus for both tricuspid and bicuspid valve (33,43). This technique has therefore fallen out of favour in recent years. Carpentier and subsequently Haydar used a continuous internal suture along the cusp insertion line. Lansac *et al*. developed double sub- and supravalvular annuloplasty techniques using 2 external rings placed at the annulus and STJ for isolated AV repair in 2003. For the subvalvular ring, the annuloplasty is performed with an open ring passed below the coronaries.



Video 1 A standardised approach to aortic valve repair.

This increases the surface of coaptation to protect the repair. Furthermore, a supravalvular annuloplasty is also performed at the level of the STJ in order to restore the STJ/annulus ratio of 1.2 (44-47). In 2009, Schäfers *et al.* described circumferential suture annuloplasty using polytetrafluoroethylene Gore-Tex 0 suture (3,48). Following Carlos Duran's description of an internal aortic ring in 1993, Rankin introduced in 2011 a rigid internal ring HAART (Hemispherical Aortic Annuloplasty Ring Technology) (49,50). The majority of these annuloplasty techniques have published in small patient numbers or for short to mid-term follow-up.

External ring aortic annuloplasty: a standardised approach to aortic valve repair

We have developed a standardised approach to AV repair which aims to resuspend the valve and to restore the ratio between STJ/annulus of 1.2. The procedure used is dependent on the phenotype of the aorta (*Figure 1*); in dilated aortic roots we perform a valve-sparing root replacement (remodeling) with subvalvular annuloplasty; in dilated ascending aorta we perform tubular aorta replacement with subvalvular annuloplasty; and in isolated AI we perform double sub- and supra-valvular annuloplasty. In each of these procedures, both the STJ and the annulus are addressed when the annulus is dilated ≥25 mm; in valve-sparing root procedures, the graft automatically provides a supravalvular STJ annuloplasty by bringing the commissures to the diameter of the tube; the same is true for tubular aorta replacement. In isolated AI, a separate expansible annuloplasty at the supravalvular STJ level in addition to a subvalvular annuloplasty at the annular level using a standardised sizing system would provide both a reduction in respective diameters as well as maintaining the geometric ratio of STJ/annulus and systolic expansibility (*Table 2*).

All 3 procedures follow the same steps by performing (I) alignment of cusp free margin; then (II) supravalvular STJ annuloplasty (remodelling for root phenotype, tubular replacement for ascending aorta phentype, STJ ring for isolated AI); followed by (III) cusp effective height assessment; and finally (IV) external ring subvalvular annuloplasty (if the annulus is ≥25 mm) (*Video 1*).

Since 2003, we have operated 482 patients using this standardized approach with 92% freedom for reoperation at 8 years similar for bicuspid and tricuspid valves according to each phenotype of the proximal aorta. Furthermore, since 2007 we have used systematic effective height assessment and expansible calibrated annuloplasty ring (Extra-Aortic; CORONEO, Inc, Montreal, QC, Canada) with the remodeling process, which has improved freedom from AI grade ≥3 (100%), re-operation (99.1%) and major adverse valve-related events (96.3%) at 7 years follow-up with similar results for bicuspid and tricuspid valve repair (51). Systolo-diastolic expansibility of the annulus was preserved following the annuloplasty (5.1%±9.5%) (52).

The CAVIAAR trial evaluated the safety of valve-sparing root surgery (VSRR) using the remodeling technique with the expansible subvalvular annuloplasty ring, and compared its outcomes with that of the mechanical Bentall procedure. It showed similar 30-day mortality in the 2 treatment groups, with a trend towards more major adverse events in the Bentall group (OR 2.52, P=0.09) (53). At 4 years, crude and propensity matched analyses confirmed that freedom from valve-related death and freedom from hemorrhagic events are significantly higher after valve repair than replacement; respectively 99% *vs.* 94% (P<0.001) and 89% *vs.* 78% (P=0.02). Furthermore, freedom from valve related reoperation was similar in the 2 groups (P=0.22).

The importance of STJ stabilization on long-term durability of isolated AI repair has been demonstrated by comparing single ring annuloplasty (subvalvular ring) to double ring annuloplasty (subvalvular and supra-valvular ring) for treatment of isolated AI repair. Double annuloplasty was associated with 100% freedom from recurrence of AI ≥ Grade 3 compared to 67% in the single annuloplasty group at 6 years (P=0.008). Moreover, use of double annuloplasty was correlated with 97% freedom from AV-related reintervention compared to 73% in the single annuloplasty group at 6 years (P=0.02). This technique showed results comparable to those of the valve-sparing procedures at 7 years (52). Long-term survival after AV repair is excellent and similar to sex- and age-matched populations (54).

Bicuspid aortic valve (BAV) repair

BAV can exist in a variety of configurations. BAV repairs in general tend to be more reproducible with the repair outcomes more predictable when compared to tricuspid aortic valves. This is because in the vast majority of cases, the fused cusp has a significant prolapse which requires plication, and the non-fused cusp can be used as a reference point with regards to free margin length.

In BAV repair, the commissural angle between the 2 true commissures is very important to the repair strategy. The commissural angle in a BAV can range anywhere between 120° (very asymmetrical valve, as in the case of a minor form of BAV where the raphe is often very short corresponding to a "tricuspid like configuration") up to 180° (the very symmetric and rare true type 0 BAV). Often it lies somewhere in the middle. We always aim for a repair strategy which produces a fully symmetrical 180° valve in all cases, with the end result being a symmetrical valve with 2 cusps of equal free margin length, thus mimicking the most stable form of a normal functioning native BAV (the so called "true type 0"). The only exceptions to this rule are those valves where the commissural angle truly lies close to 120° with "tricuspid like configuration".

In order to create a symmetrical 180° valve, the inter-commissural distance must be adjusted. In most BAVs, the fused sinus is larger than the non-fused sinus. We therefore plicate the fused sinus thereby equalising the inter-commissural distance. We also place the 2 commissures at exactly 180° to each on the STJ ring. These 2 manoeuvres help to create a symmetrical valve configuration.

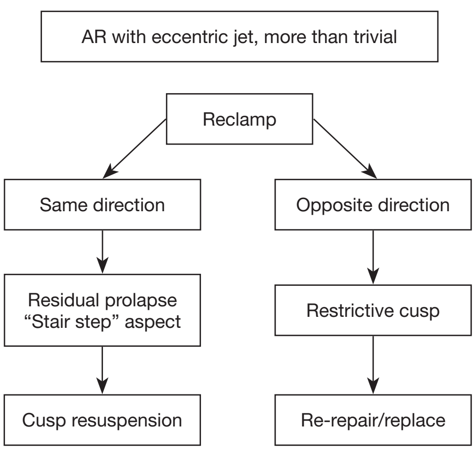


Figure 6 Management of residual eccentric AI. AR, aortic regurgitation.

What is a good repair result, and when to reclamp?

Immediately after removing the cross-clamp, we perform trans-oesophageal echocardiography to assess for AI. This period of time between removing the cross-clamp and discontinuing cardiopulmonary bypass is when the repaired AV is under the most stress. This is because non-pulsatile flow from the arterial cannula is continuously pushing back on the valve. We find that if there is no residual AI at this stage, the results of the repair will be satisfactory once cardiopulmonary bypass has been discontinued.

We will only accept no residual AI or trace AI with a central jet. Any eccentric jet, even if trivial, is not accepted as long-term results will be poor. Using 3D echo, we will be satisfied with an effective height eH ≥9 mm, coaptation height (cH) ≥4 mm, an aortic annulus <25 mm, and mean transaortic pressure gradient <10 mmHg (52).

The presence of more than trivial AI after repair, or an eccentric jet, defines a suboptimal result. In this case, the AI jet direction is crucial for subsequent surgical management.

Residual AI with an eccentric jet (Figure 6, Table 2)

Most instances of residual AI (more than trace) with an

Table 2 Isolated AI repair sizing criteria for subvalvular aortic and sinotubular ring size

	Aortic annulus diameter (Hegar dilator)			
	25–27 mm	28–30 mm	31–35 mm	≥36 mm
Subvalvular aortic ring (mm)	25	27	29	31
STJ extra aortic ring (mm)	25	27	29	31

STJ, sinotubular junction; AI, aortic insufficiency.

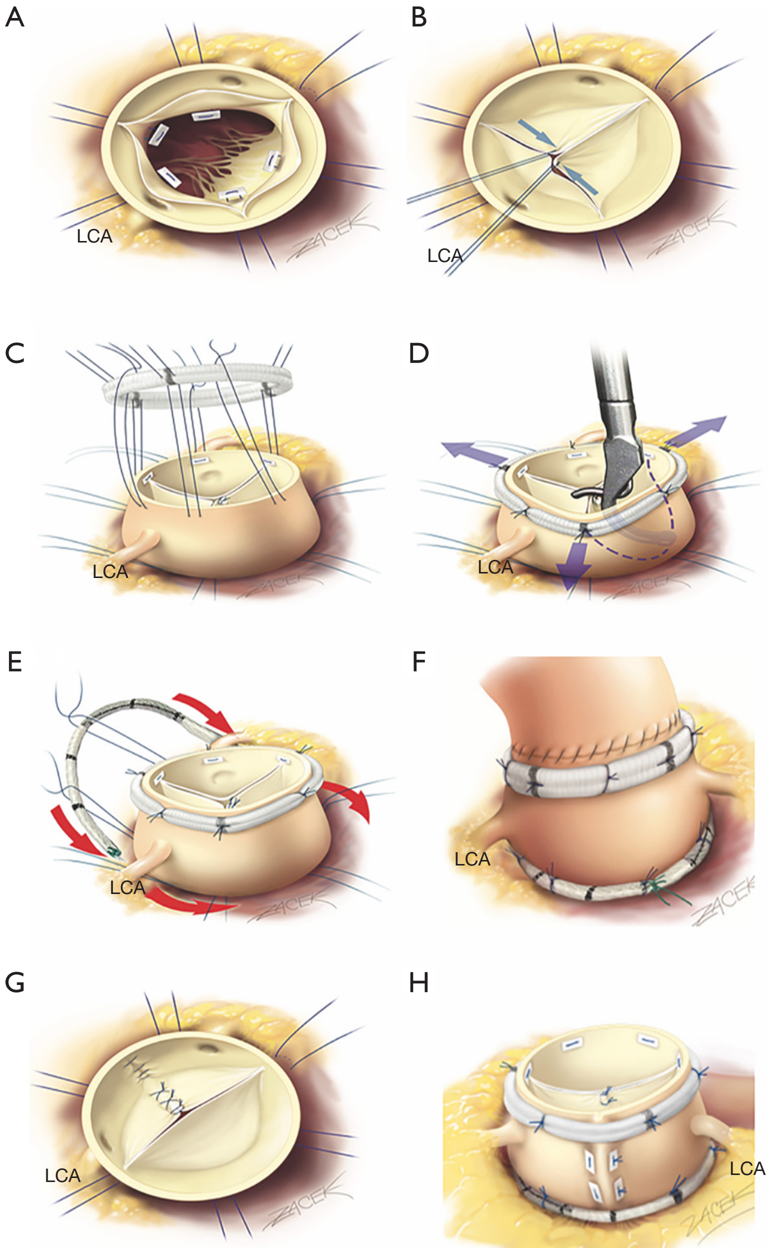


Figure 7 Standardized steps in isolated aortic valve repair with double ring repair. (A) 6 'U' stitches are circumferentially placed in the subvalvular plane except at the level of the commissure between the non- and right coronary sinuses, where it is placed externally. (B) Alignment of cusp free edges. (C) Sinotubular junction ring placement. (D) Cusp resuspension (effective height >9 mm). (E) Open ring placement below the coronary arteries. (F) Aortotomy closed; final appearance. (G) Central plication of excess tissue for bicuspid repair. (H) In the case of asymmetric bicuspid commissural orientation <170, a plication of the sinus at the level of the raphe is added. LCA, left coronary artery.

eccentric jet are an indication to reclamp for a second AV repair, or valve replacement (*Figure 7*). Eccentric AI may be due to residual cusp prolapse (typically with a "stair step" aspect), which may be treated by repeat cusp resuspension. On the other hand, eccentric AI might be due to cusp restriction, to be treated by the release of some resuspension

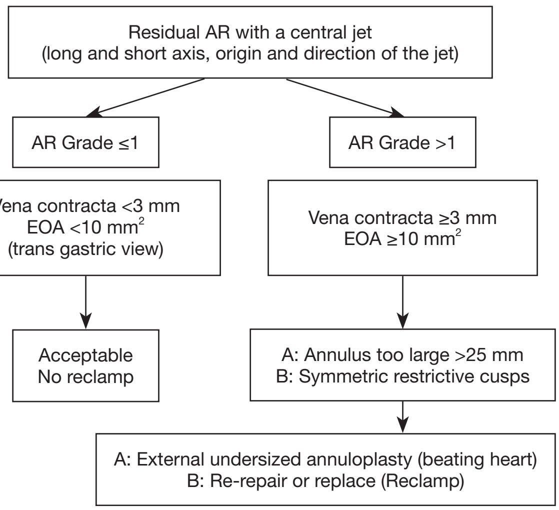


Figure 8 Management of residual central AI. AR, aortic regurgitation.

stitches if possible, or by AV replacement.

AI with a central jet (Figure 8)

Residual central AI is acceptable if it's not more than trivial, meaning only a limited extension of the color Doppler jet in the LV outflow tract, far from the free edge of the anterior mitral leaflet. Otherwise, the possible causes of significant (grade ≥1/4) residual central AI may be due to an insufficient aortic annuloplasty (annulus ≥25 mm of diameter in systole), or symmetrical over-restriction of the aortic cusps. In the case of insufficient annuloplasty, this can be treated by further undersizing the ring on the beating heart. In the case of symmetrical over-restricted cusps, this can be treated by releasing some of the resuspension stitches if possible, or by AV replacement.

Conclusions

We now have the evidence to show that AV repair is safe, reduces valve-related mortality compared to prosthetic valve replacement, produces better quality of life and provides similar life expectancy as that of the general population. The dissemination and uptake of these techniques very much depends on their standardisation and reproducibility, as well as uniform clinical reporting to evaluate long-term patient outcomes. As part of the standardised technique to treat AI, a calibrated annuloplasty at both sub- and supravalvular levels helps to restore the STJ/annulus ratio, and can be performed according to the different aortic phenotypes such as dilated root, dilated ascending aorta, and isolated AI.

To further analyse the long-term benefits of aortic valve repair, we must continue to search for high quality real-world data from as many institutions as possible. This is the vision of the AVIATOR registry (www.heartvalvesociety.org/AVIATOR).

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Footnote

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