



Aortic valve repair for aortic regurgitation and preoperative echocardiographic assessment

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Abstract

Aortic valvuloplasty (AVP) has been performed less frequently than mitral valvuloplasty. The survival benefit of AVP over replacement has been demonstrated. Therefore, standardization of AVP is crucial for its widespread adoption. The hemodynamic advantage of AVP of preserving the native aortic valve may be one reason for the survival benefit. Recent guidelines still recommend AVP in selected cases compared with the less restricted recommendation for mitral valvuloplasty, although recent studies have proposed earlier indication for surgical intervention. Indication for aortic root replacement is also still conservative, especially in Japan. However, more liberal root replacement should be recommended for better repair when AVP is indicated. Theoretically, all aortic regurgitation lesions can be repaired with acceptable durability. However, restricted cusp should be extended by a pericardial patch, which itself has emerged as a risk of recurrence. Therefore, indications for aortic regurgitation for type III lesions should be determined carefully. Special consideration is crucial for bicuspid aortic valve repair; prevention of postoperative stenosis is especially important. Arrangement of the commissure position is the most important consideration for this purpose, although it remains controversial. Therefore, detailed diagnosis is important in planning AVP, and echocardiography plays a key role in this process.

Keywords Aortic valve repair · Valve-preserving root replacement · Echocardiography · Surgical indication · Operative technique

Introduction

Current status of aortic valve repair

The number of mitral valve repair operations in Japan is increasing, and at present they account for up to two-thirds of all mitral valve surgeries (68% in 2014) [1]. However, aortic valve repair is less common than mitral valve repair. The Euro Heart Survey on valvular heart disease revealed that aortic valvuloplasty (AVP) was used in only 1.7% of aortic valve procedures performed for aortic regurgitation (AR) in 2001 [2]. In the annual updated registry of the German Society for Thoracic and Cardiovascular Surgery, AVP was employed in 1.0% of aortic valve procedures, and valve-sparing root replacement (VSRR) was utilized in 23.7% of

aortic root procedures in 2015 [3]. A report from a Society of Thoracic Surgeons database study in the USA indicated that VSRR was used in 14% of cases, and the annual number of VSRR procedures reached a plateau from 2007 to 2009 [4].

Japan shows the same trend, but the annual number of AVP procedures is decreasing. AVP was performed in 4.0% of isolated aortic valve surgeries in 2012 [5], but decreased to 2.9% in 2014 [1]. Instead, aortic valve replacement (AVR) with tissue heart valve has been increasing. However, these data were analyzed without taking into account the etiology of the aortic valve pathology. According to our original nationwide survey, AVP was performed in 8% of patients with AR and VSRR for 34% of root replacements for AR during 2014 in Japan, which are greater than the rates reported in other countries [6].

These observations raise questions regarding why aortic valve repair has been performed so infrequently in comparison to mitral valve repair. There are a number of anatomical and technical reasons for this, as shown in Table 1. However, since cusp geometry began to be evaluated not subjectively

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Table 1 Anatomical and technical differences between mitral and aortic valve repair

	Mitral valve repair	Aortic valve repair
Cusp volume	Abundant	Scarce
Cusp thickness	Thick	Thin
Annuloplasty	Yes	No → Yes
Chordal replacement	Yes	No
Cut and suture	Yes	Yes
Cusp coaptation	1 plane	3 planes (TAV)
Evaluation	Water test	Effective height

TAV tricuspid aortic valve

but objectively (i.e., effective height: eH) [7], aortic valve repair has become reproducible and is more commonly used than before. Classification of the etiology of AR is also helpful for the widespread adoption of aortic valve repair (Fig. 1) [8]. Nevertheless, the relatively long learning curve may still prevent widespread application of AVP at the general community level [9]. Therefore, standardization of AVP is crucial for its widespread adoption [10].

Impact of aortic valve repair

There is evidence that mitral valve repair has a survival benefit over replacement, but no such evidence is available for AVP. Two recent observational studies demonstrated the

survival benefit of AVP over replacement. One study performed in Brussels, Belgium, showed a 27% survival benefit of AVP over replacement at 9 years in propensity score-matched patients with AR in their 60s [11]. Another study from Toronto, Canada, showed up to a 20% survival benefit of VSRR over root replacement regardless of valve type at 20 years in unmatched young patients less than 50 years old with root aneurysm [12]. One reason for the survival benefit of AVP over replacement may be structural valve deterioration of the tissue heart valve, especially in young patients [13]. Another may be prosthesis- or anticoagulation-related adverse events, especially in cases with a mechanical prosthesis [14]. However, there may be another possible mechanism for the observed survival differences. 40 years ago, Rahimtoola reported that AVR introduced new problems in patients [15]. That is, patients with AR have a normal aortic valve area. However, even the latest mechanical valve model cannot surpass the native aortic valve area. Furthermore, use of a biological valve has a risk of prosthesis–patient mismatch.

We investigated postoperative hemodynamics at 1–2 years after either AVP or AVR in propensity score-matched patients with AR (*n* = 24 each). The postoperative transvalvular gradient was significantly higher after AVR than AVP. Postoperative aortic valve area was also significantly smaller after AVR than AVP. This trend was even more prominent for biological valves. These differences do not seem remarkable, but the gradient increases with higher

AI Class	Type I Normal cusp motion with FAA dilatation or cusp perforation				Type II Cusp Prolapse	Type III Cusp Restriction
	1a	1b	1c	1d		
Mechanism						
Repair Techniques (Primary)	STJ remodeling <i>Ascending aortic graft</i>	Aortic Valve sparing: <i>Reimplantation or Remodeling with SCA</i>	SCA	Patch Repair <i>Autologous or bovine pericardium</i>	Prolapse Repair <i>Plication</i> <i>Triangular resection</i> <i>Free margin Resuspension</i> <i>Patch</i>	Leaflet Repair <i>Shaving</i> <i>Decalcificatio</i> <i>Patch</i>
(Secondary)	SCA		STJ Annuloplasty	SCA	SCA	SCA

Fig. 1 Classification of the etiology of aortic regurgitation Reproduced with permission from [8]

cardiac output [16], which makes it clinically relevant in young active patients. However, it is well known that the gradient after AVP increases over time, especially in patients with bicuspid valve or after patch repair [17, 18]. Importantly, a higher gradient is associated with late recurrence after AVP [19]. Thus, the postoperative aortic valve area should be kept as large as possible when AVP is performed, especially in young and active AR patients.

Indication for aortic valve repair

Surgical indication for AR

Surgical indication for AR should be determined by left ventricular (LV) dimension. The AHA/ACC guidelines published in 2014 recommend surgical intervention for AR in cases with LV end-diastolic diameter over 65 mm or LV end-systolic diameter over 50 mm [20], whereas the European guidelines published in 2017 still recommend an LV end-diastolic diameter of 70 mm for surgical intervention [21]. However, when AVP is indicated, early intervention before the development of cusp degeneration is favorable. Currently, stage C2 is class I or IIa recommendation, whereas stage C1 is class IIb in the AHA/ACC guidelines. However, lower left ventricular ejection fraction is associated with poorer early and late outcomes, and therefore the operation should ideally be performed before deterioration of LV function [22, 23]. Therefore, recent studies have proposed earlier surgical intervention [24]. A survival benefit can be gained even with LV end-systolic diameter per body surface area of 20 mm/m² or smaller or LV ejection fraction of 55% or more [25, 26].

Surgical indication for aortic root enlargement

Western guidelines recommend root replacement when the proximal aortic diameter exceeds 50 mm. Surgical intervention is even indicated for a diameter of 40–50 mm in cases with an aortic growth rate of 3–5 mm/year or connective tissue disease [27, 28]. The Japanese guidelines seem more conservative even though Japanese patients are smaller. Proximal aortic diameter over 60 mm is defined as class I recommendation, and an aortic growth rate of 5 mm every 6 months is borderline in the Japanese guidelines [29, 30].

When surgical intervention is indicated for the aortic valve, root replacement is recommended in cases with proximal aortic diameter over 45 mm in Western guidelines and 50 mm in the Japanese guidelines [27–30]. However, when AVP is planned, this threshold can be lowered. In cases with bicuspid aortic valve (BAV), in particular, arrangement of the commissure configuration may lead to not only better cusp coaptation, but also favorable postoperative hemodynamics. Indeed, better late outcomes have been achieved

with than without root replacement in BAV patients [31, 32]. Another reason may be the fact that root enlargement has emerged as a risk factor for late recurrence [32–34]. Therefore, some institutions use a surgical threshold of 43 mm in diameter [32, 34].

Detailed preoperative measurement of the aortic root geometry is crucial for the planning of AVP. Three-dimensional observation is essential because the aortic annulus is elliptical. Not only the diameter, but also the configuration should be observed. These findings should be compared with computed tomographic findings for accurate diagnosis.

Indication for AVP

Currently, AR of all etiologies can theoretically be repaired with acceptable results (Fig. 1) [8]. However, freedom from reoperation for type III lesions seems to be inferior to other types [8]. Furthermore, use of a pericardial patch was identified as a risk factor for recurrence [32, 34]. Nonetheless, cusp extension is necessary to avoid AVR, especially for young patients. Schäfers et al., based in Germany, proposed a geometric height (GH) of 16 mm for tricuspid aortic valve (TAV) and 19 mm for BAV as cutoff values to perform AVP [35]. However, it should be noted that GH of Japanese patients is 1–2 mm shorter than that in German patients, and the cutoff value of GH should take the patient's body size into consideration.

Therefore, both GH and pliability of each cusp should be examined carefully prior to the operation. However, GH is generally underestimated regardless of imaging modality. Intraoperative findings should be fed back to preoperative findings, and discrepancies between them should be understood within the heart team, which will enable better preoperative prediction of actual GH.

Technique of AVP and perioperative assessment

Type Ia

Type Ia AR can easily be diagnosed by observing central straight jet due to poor cusp coaptation caused by tethering despite sufficient GH and eH (Fig. 2). This can be repaired simply by remodeling of the sinotubular junction (STJ) [36, 37]. However, excessive reduction of STJ diameter will be associated with iatrogenic cusp prolapse [38]. Thus, echocardiographers should also carefully check the postoperative cusp configuration.

Type Ib

Type Ib involves dilatation of both STJ and Valsalva sinus, and frequently also the basal ring (Fig. 3). This can be repaired by either aortic valve reimplantation or aortic root

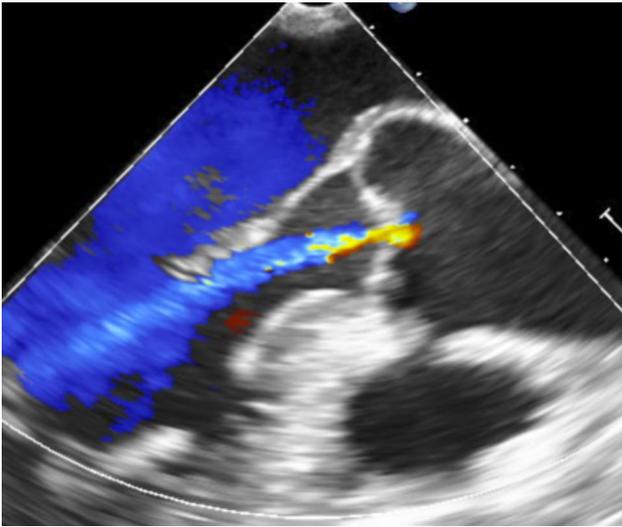
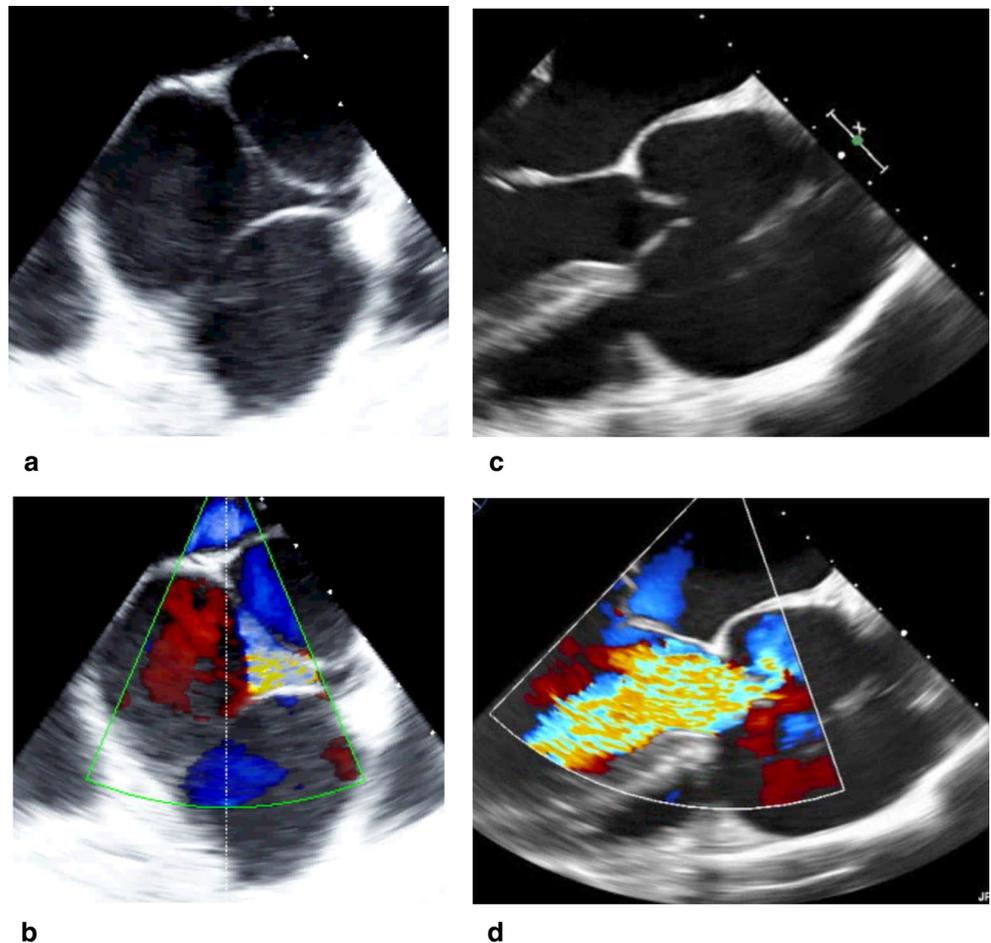


Fig. 2 Central straight jet due to poor cusp coaptation caused by type Ia lesion

remodeling [39, 40]. Each has a number of advantages and disadvantages, but these techniques have been modified and

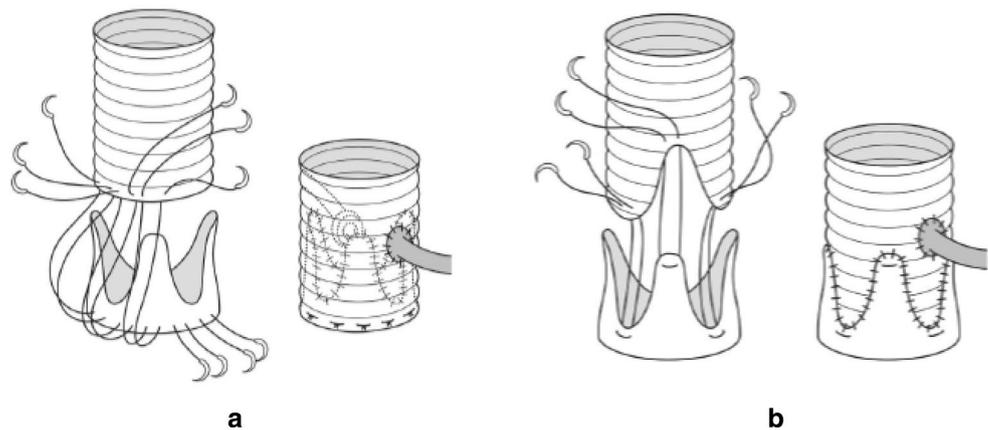
Fig. 3 **a, c** Loss of coaptation caused by cusp tethering due to dilatation of both sinotubular junction and Valsalva sinus. **b, d** Severe aortic regurgitation through loss of coaptation zone



improved and are therefore equivalent with regard to valve durability (Fig. 4) [10, 41]. The reimplantation technique provides secure annular stabilization, but inferior transvalvular hemodynamics, which can be resolved by the use of a graft with sinuses. Due to the use of two-layer anastomosis, fair hemostasis is generally obtained, but it results in a longer procedural time. The remodeling technique lacks annular stabilization, which can be improved by the addition of annuloplasty. Preservation of interleaflet triangles is advantageous for transvalvular hemodynamics. The risk of bleeding is considered to be higher due to the single suture line, which can be prevented by firm annulus suturing.

Preoperative diagnosis is relatively straightforward, but care must be taken not to overlook concomitant type II lesions. It is well known that intercommissural distance is highly variable between individuals, especially with the stretched aortic root [42]. Shortening of the longer intercommissural distance will result in reducing eH of the corresponding cusp. Thus, symmetrical realignment of three commissures has the potential risk of producing iatrogenic cusp prolapse [38]. It would be of great interest to observe cusp motion after valve-sparing root replacement to evaluate the physiological role of the neosinus [43].

Fig. 4 Schematic diagram of aortic valve reimplantation (a) and aortic root remodeling (b) Reproduced with permission from [41]



Type Ic

Type Ic lesions are caused by dilatation of the aortic annulus resulting in loss of cusp coaptation, which can be treated by annuloplasty (Fig. 5). Various annuloplasty approaches have been advocated, and the widely accepted traditional method is partial commissuroplasty (so-called Cabrol stitch) (Fig. 6) [44]. However, partial annular reduction is considered suboptimal, and so circular annuloplasty is currently widely accepted. In Japan, external suture annuloplasty [45], external flexible ring annuloplasty [46], and internal flexible ring annuloplasty [47, 48] are clinically available (Fig. 6). Each approach has both advantages and disadvantages, but as it is not the focus of this review, please refer to other articles for details [49].

Preoperative assessment requires not only annulus size, but also annular configuration because localized annular dilatation is occasionally the cause of AR. Therefore, three-dimensional analysis is essential. It is also important to observe whether or not the basal ring level is certainly

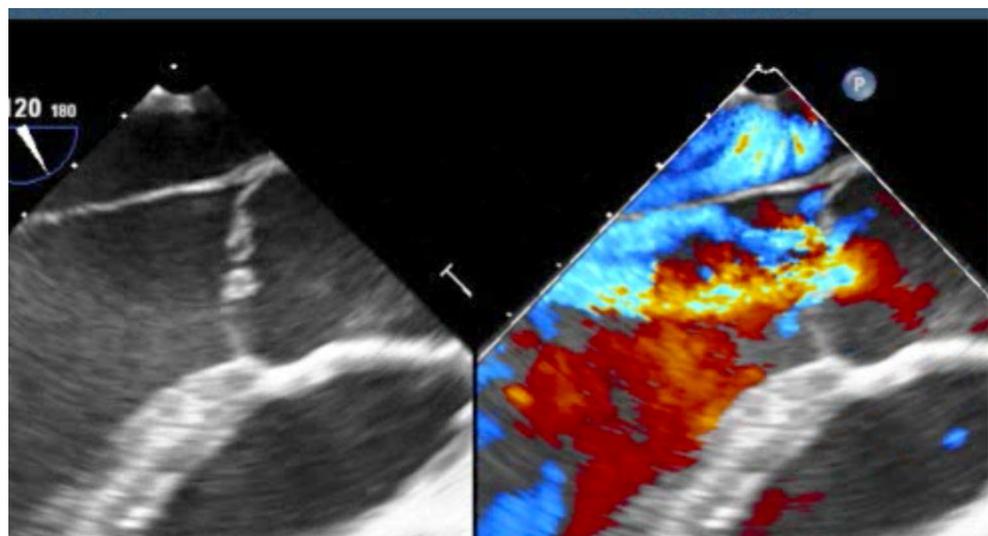
reduced after annuloplasty. Inadequate dissection in the right coronary sinus is associated with tilting positioning of the ring, which is not optimal for annular stabilization [50].

Type Id

Fenestration or perforation can be repaired by simply using a pericardial patch with favorable long-term results. Up to three defects on up to two cusps can be closed with acceptable durability [51].

It is difficult to accurately diagnose a type Id lesion in cases with a combined type II lesion. An eccentric jet from around the commissure strongly suggests fenestration or strand rupture (Fig. 7). With a history of infective endocarditis, perforation is highly suspected. Preoperative diagnosis is almost impossible in cases with fenestration within the cusp coaptation zone that does not contribute to AR. Even if it contributes to AR, the AR can disappear with improvement of the cusp coaptation depth (Fig. 7). Therefore, surgeons

Fig. 5 Type Ic lesions are caused by dilatation of the aortic annulus, resulting in loss of cusp coaptation and central straight jet



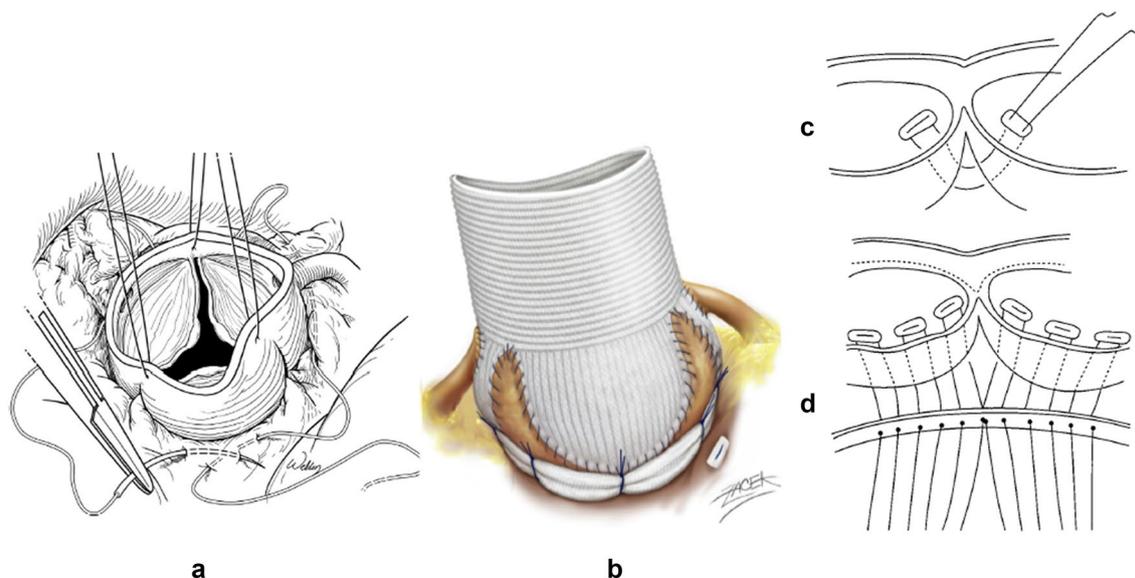


Fig. 6 Currently clinically available annuloplasty in Japan: external suture annuloplasty (a), external flexible ring annuloplasty (b), subcommissural annuloplasty (c), and internal flexible ring annuloplasty (d)

a reproduced with permission from [45], b reproduced with permission from [46], c reproduced with permission from [48], d reproduced with permission from [48]

should decide during AVP whether or not intervention for a type Id lesion is necessary.

Type II

Type II lesions are the most common cause of AR and are frequently combined with other lesions. The fundamental approach to correct such lesions is to shorten the free margin length. Classically, this was performed at the commissure site (so-called Trusler stitch) [52]. However, this approach has now been abandoned because diastolic stress is highest at the commissure [53]. Triangular resection is frequently performed for BAV, but is not advisable for TAV except in cases with heavy calcification because the cusp tissue is normally very thin in TAV patients [54]. Therefore, central cusp plication is currently widely accepted because the free margin length can be adjusted in a stepwise manner, and it can easily be removed in cases with excessive correction [55] (Fig. 8a). Resuspension of the free margin using an expanded polytetrafluoroethylene suture is another approach, but it is technically demanding to precisely adjust the free margin length [56, 57] (Fig. 8b). The key to successful repair is to achieve the same eH for each cusp. For Western subjects, a 9–10-mm eH is recommended, while 8 mm is also acceptable for Japanese patients because of their generally shorter GH [7]. It should be determined after taking the GH of each cusp and the target annulus diameter into consideration.

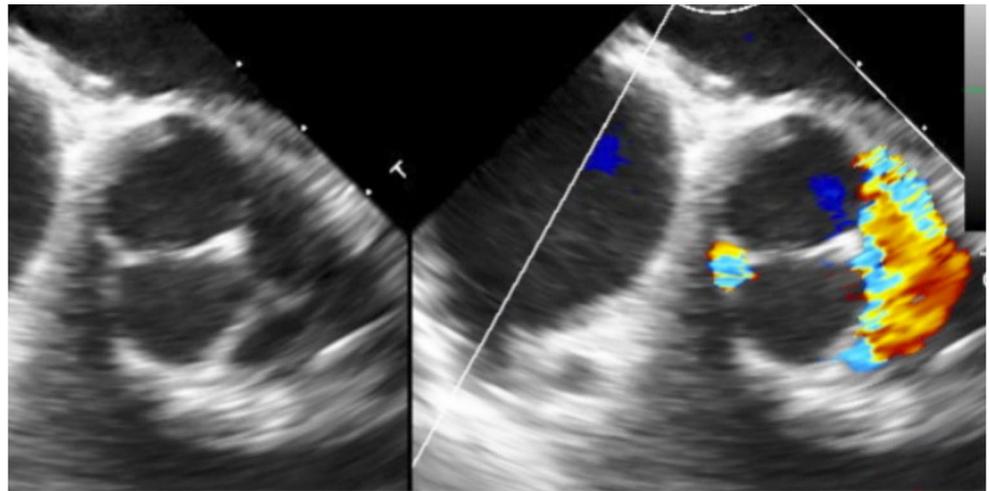
Type II lesions can easily be diagnosed by the presence of an eccentric jet from the center of the prolapsed cusp

due to reduced eH. A characteristic finding is cusp bending caused by a long history of AR [58] (Fig. 9a, b). Occasionally, the bending site becomes thickened (so-called fibrous band), which is regarded as unfavorable but not a contraindication for AVP (Fig. 9c). As described previously, iatrogenic prolapse should always be assessed by postoperative echocardiography.

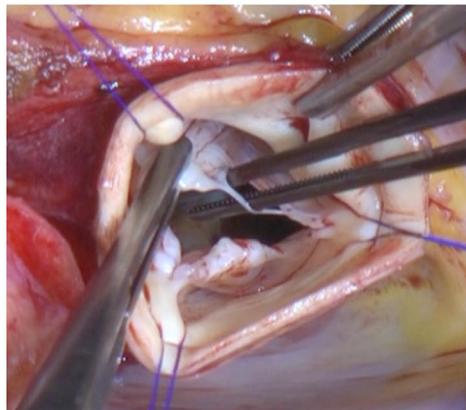
Type III

Restricted cusp should be extended by a pericardial patch [59] (Fig. 10), but the pericardial patch itself has emerged as a risk of recurrence, and therefore the indications for AR for a type III lesion should be determined carefully [32, 34]. Preoperative diagnosis plays a key role in planning the surgical strategy for type III lesions. In general, GH less than 16 mm in TAV and 19 mm in BAV is considered contraindicated for AVP unless cusp extension is performed [35]. However, preoperative measurements always underestimate GH regardless of diagnostic modality. It is necessary to understand the discrepancy between preoperative and intraoperative measurements in routine practice and to estimate the actual GH from preoperative imaging. Even if GH is sufficient, partial calcification or thickening should also be assessed. AVP should generally be contraindicated if calcification is observed in more than half of the area of one cusp.

Fig. 7 **a** Eccentric jet from the commissure between the right and non-coronary cusp strongly suggested fenestration or strand rupture. **b** Fenestration at the right coronary cusp was found. **c** Fenestration was covered within a coaptation zone between the right and non-coronary cusp, and no further surgical intervention was necessary



a

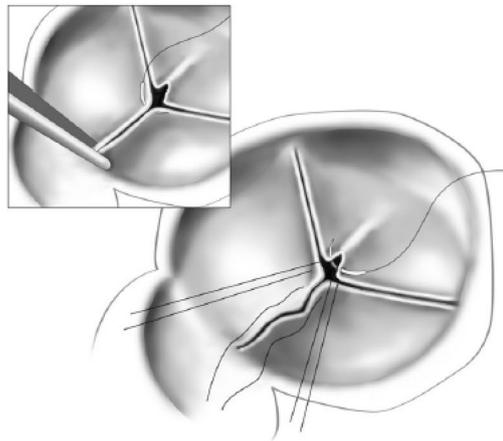


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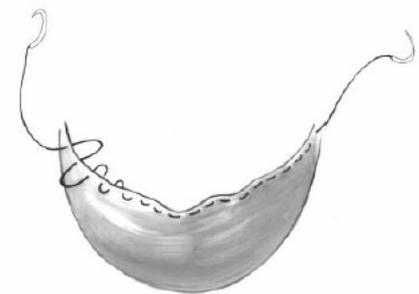


c

Fig. 8 **a** Central cusp plication to correct cusp prolapse due to type II lesion. **b** Resuspension of the free margin to correct cusp prolapse due to type II lesion (**a**) Reproduced with permission from [51], (**b**) reproduced with permission from [57]



a



b

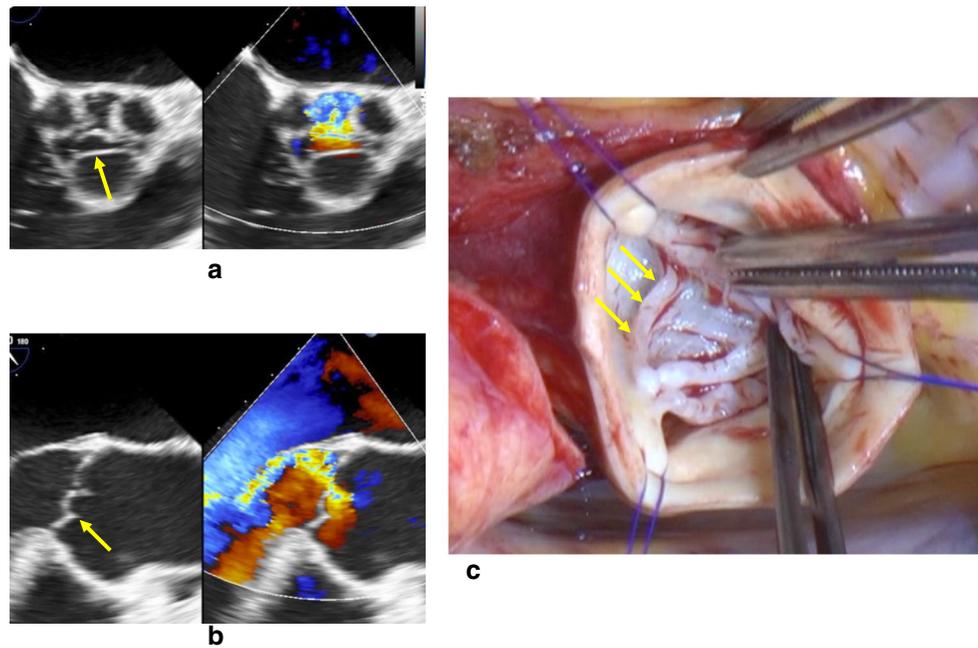
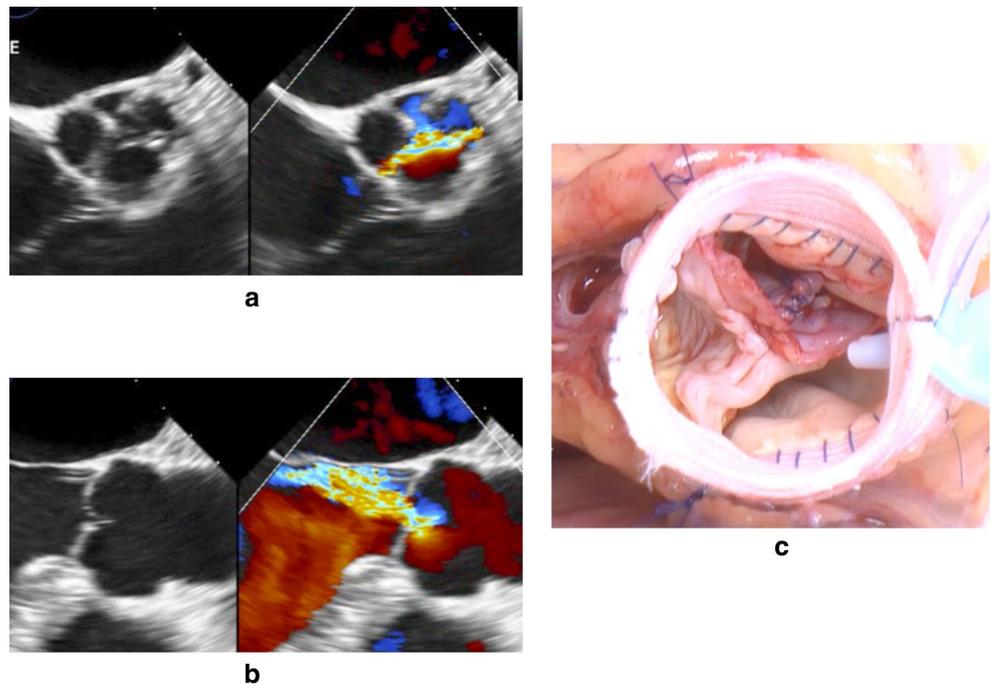


Fig. 9 **a** Cusp bending (yellow arrow) caused by a long history of aortic regurgitation due to right coronary cusp prolapse. **b** Eccentric jet from the center of the prolapsed cusp due to reduced effective height. The yellow arrow indicates cusp bending of the right coronary

cusp. **c** Thickened bending site of the left coronary cusp (so-called “fibrous band”) (yellow arrow) (a) Reproduced with permission from [58], (b) reproduced with permission from [58]

Fig. 10 **a, b** Eccentric jet from the restricted right coronary cusp due to type III lesion. **c** Extension of the right coronary cusp with an autologous pericardial patch



Bicuspid aortic valve

Special consideration is crucial for BAV repair. The key issue is to prevent postoperative stenosis, because a postoperative

peak transvalvular gradient more than 20 mmHg is considered to be a risk factor for recurrence [19] and the gradient increases over time [17]. Therefore, three points should be checked preoperatively in planning BAV repair:

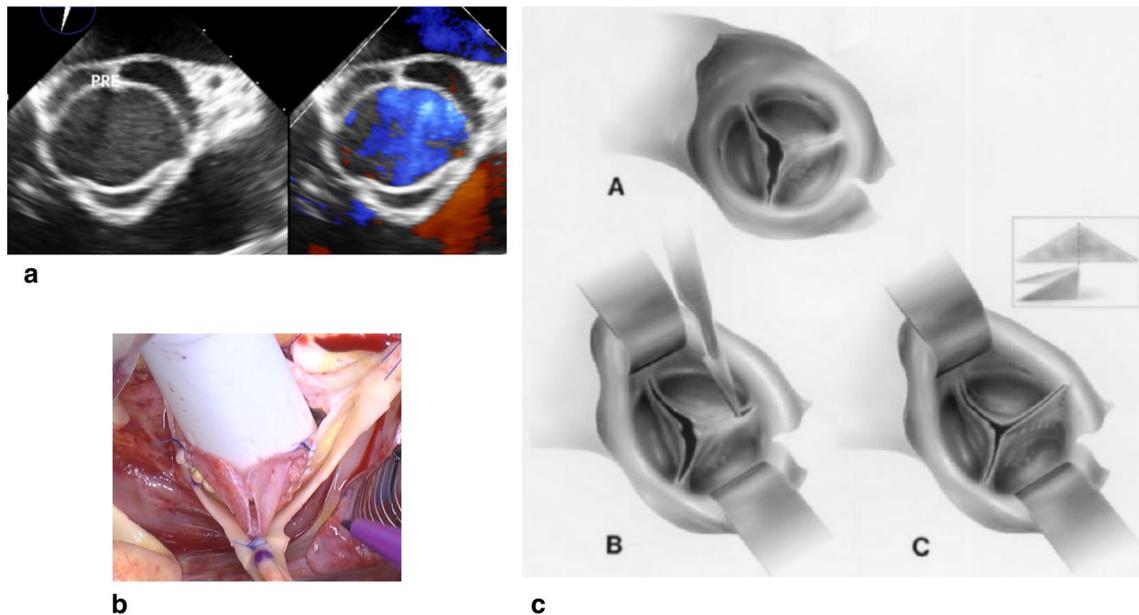


Fig. 11 **a** The bicuspid aortic valve with lower commissure angle near 120° (i.e., incomplete fusion type). **b** Tricuspidization of the incomplete fusion-type bicuspid aortic valve using autologous pericardial patches at the left and non-coronary cusp. **c** Schematic dia-

gram of tricuspidization of the incomplete fusion-type bicuspid aortic valve (**a**) reproduced with permission from [58], (**b**) reproduced with permission from [58], (**c**) reproduced with permission from [62]

Root replacement It is advisable to shorten the intercommissural distance and arrange the commissures at a higher position to improve cusp motion. Therefore, the threshold for root replacement should be lowered for BAV repair. For BAV patients at high risk for postoperative stenosis, root replacement can be considered for Valsalva sinus diameter less than 40 mm. Accurate preoperative measurement of Valsalva sinus diameter by three-dimensional imaging is therefore essential.

Commissure angle A commissure angle of 180° provides the most physiological and efficient transvalvular hemodynamics [60, 61], and that over 160° is associated with better long-term durability after AVP [32]. In cases with a lower commissure angle close to 120° (i.e., incomplete fusion type), frequent plication of the fused cusp may be associated with relevant stenosis. Tricuspidization using a pericardial patch is one solution that can be applied in this scenario [58, 62] (Fig. 11). On the other hand, as noted previously, use of a pericardial patch is a risk factor for recurrence [32, 34]. Therefore, measurement of commissure angle is highly recommended to predict the risk of stenosis. In addition, the aortic valve area of the non-fused cusp alone is also useful to estimate the postoperative transvalvular hemodynamics.

Use of a patch Calcification or thickening is frequently observed in the raphe of fused cusps. To improve cusp motion, slicing or resection is necessary in most cases. When wide resection is mandatory, a pericardial patch is required to cover the defect (Fig. 12). As described above, use of a patch should be determined carefully in optimal candidates. Therefore, preoperative observation of the extent of calcification or thickening may play a crucial role in planning of AVP.

Conclusion

All AR lesions can theoretically be repaired, although some lesions are still challenging and long-term durability is unclear. Therefore, detailed diagnosis is important in planning AVP, and echocardiography plays a key role in this process. Repeated feedback and adequate discussion between the echocardiographers and surgeons will further improve the success rate and durability of AVP. It is necessary for these professionals to use common terms and have a detailed understanding of the pathophysiology of the aortic valve. This review should be helpful in achieving this goal.

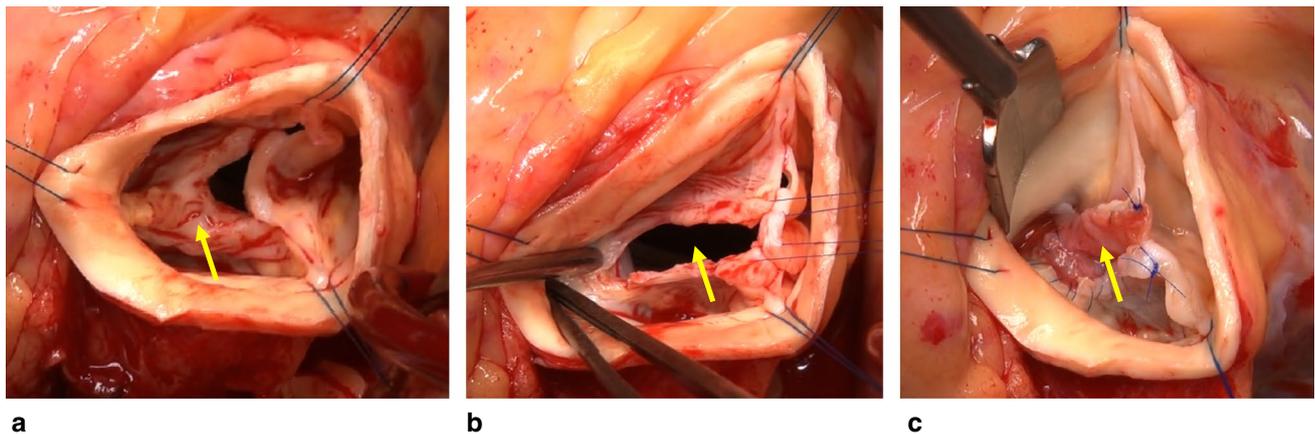


Fig. 12 **a** The calcified raphe of the fused cusp of the bicuspid aortic valve (yellow arrow). **b** A large defect after resecting the calcified raphe (yellow arrow). **c** Substitution of a defect using an autologous pericardial patch (yellow arrow)

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Compliance with ethical standards

Conflict of interest The author declares that there are no conflicts of interest related to this study.

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