

**Review
Article**

Valve-sparing Aortic Root Replacement

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The aortic root has a unique 3-dimensional configuration and the distinctive function of supporting the aortic valve and blood vessels. The sinuses of Valsalva are crucial to create appropriate eddy currents that are important in initiating and coordinating aortic valve closure and promoting coronary artery blood flow. Most aneurysms in the aortic root are associated with degenerative changes in the elastic media rather than atherosclerosis. Valve-sparing root repair has become widely accepted, although the Bentall procedure remains the gold standard. Because reimplantation using the Valsalva graft allows root geometry to be retained and theoretically and practically prevents recurrent aortic valve regurgitation, it is considered the most reliable and preferred technique among various valve-sparing aortic root repair procedures.

Anatomy of the Aortic Root

The aortic root is the most proximal part of the aorta. It has a unique 3-dimensional (3D) configuration with a clover-like dilation of the sinuses of Valsalva within which the aortic valve forms a three-pronged crown. The attachment of each valve leaflet to the aortic wall is semilunar, running from the basal attachment within the left ventricle to the distal attachment at the sinotubular (ST) junction. The virtual circle connecting the lowest point on each semilunar attachment is called the basal ring. The posterior half of the basal ring (including the base of the non-coronary sinus) is fibrous, and the anterior half (including the base of the left and right coronary sinuses) is muscular. The fibrous portion is considered weaker and easy to dilate. The semilunar attachment forms a hemodynamic (but not an anatomical) junction between the left ventricle and the aorta. The anatomical ventriculo-aortic junction is the circle lying a little above

the basal ring (**Fig. 1**).¹⁾ The bundle of His lies immediately below the membranous ventricular septum that lies immediately beneath the commissure between the right and noncoronary cusps (**Fig. 2**).²⁻⁴⁾ The diameter of the aorta at the ST junction is 81% of the diameter at the aortic sinuses, and 97% at the basal ring.⁵⁾

Function of Aortic Root

The aortic root not only channels blood but also supports the aortic valve leaflets. The clover-like dilation of sinuses of Valsalva is crucial to create appropriate eddy currents in the supra-ventricular region, which are important for initiating and coordinating aortic valve closure and promoting coronary artery blood flow.

Etiology and Pathology of the Aortic Root

Most aneurysms in the aortic root are associated with degenerative changes in the elastic media, although atherosclerosis is the major etiology of aneurysms in other regions of the aorta. This probably correlates with the higher concentration of elastic fibers in the media of the aortic root. Cystic medial degeneration, or elastic fiber fragmentation and smooth muscle loss, are typical of the histological characteristics of root aneurysms. Aortic root aneurysms might cause not only aortic rupture and dissection but also secondary aortic valve regurgitation (AR) as a result of a distorted 3D conformation of the aortic

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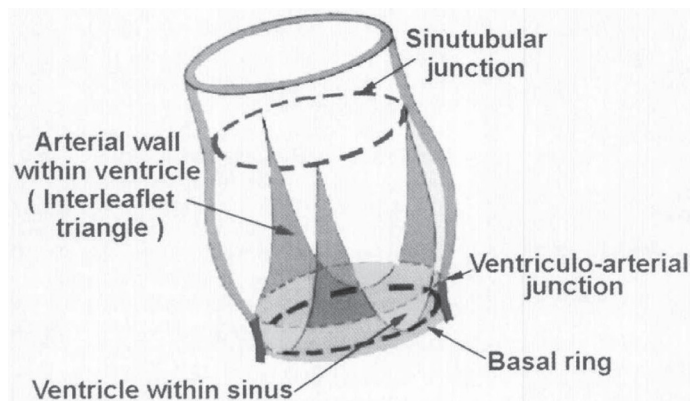


Fig. 1 Anatomy of the aortic root.¹⁾

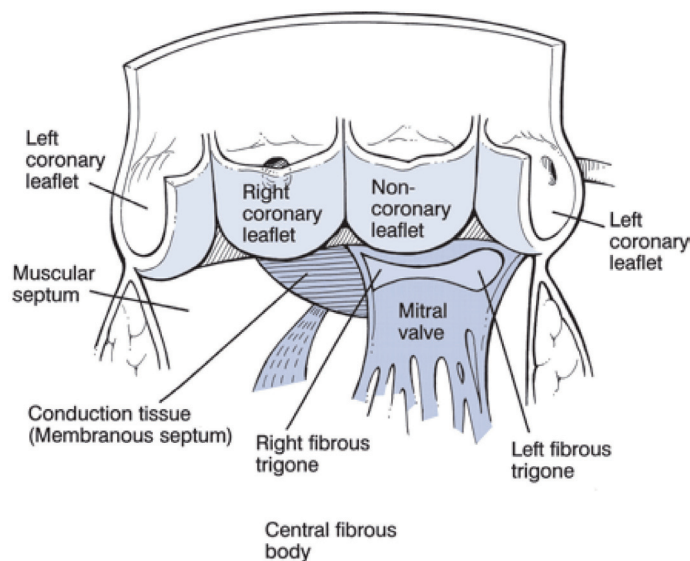


Fig. 2 Relationship between aortic valve leaflets and structures underlying commissures.⁴⁾

root and aortic valve complex. Annuloaortic ectasia and aortic dissection are common causes of mortality in patients with Marfan syndrome. Aneurysms associated with the bicuspid aortic valve are also a common pathology.

Bentall Procedure, Remodeling and Reimplantation

The gold standard for treating aortic root pathology has been the Bentall procedure⁶⁾ and modifications.⁷⁻⁹⁾ This operation involves replacement of the entire aortic root and valve with a composite valve graft and reimplantation of the coronary buttons. The early- and long-term results of this procedure are excellent.^{10, 11)}

However, surgeons are not always willing to excise and replace valve leaflets that often appear morphologically normal. Yacoub and colleagues^{12, 13)} and David and colleagues¹⁴⁾ introduced valve-sparing aortic root replacement (VSRR), which has the greatest advantage of eliminating the need for lifelong anticoagulation therapy and preventing potential risks related to prosthetic valves. If concomitant AR is caused by disruption of the leaflets from their coaptation while enlarging the aortic root, then AR could be repaired by restoring the original root geometry without replacing the valves.

The VSRR procedures consist of remodeling and reimplantation. Remodeling is also known as the Yacoub procedure in which a scalloped graft is sutured to the sinus remnant around the attachment of the valve leaflets

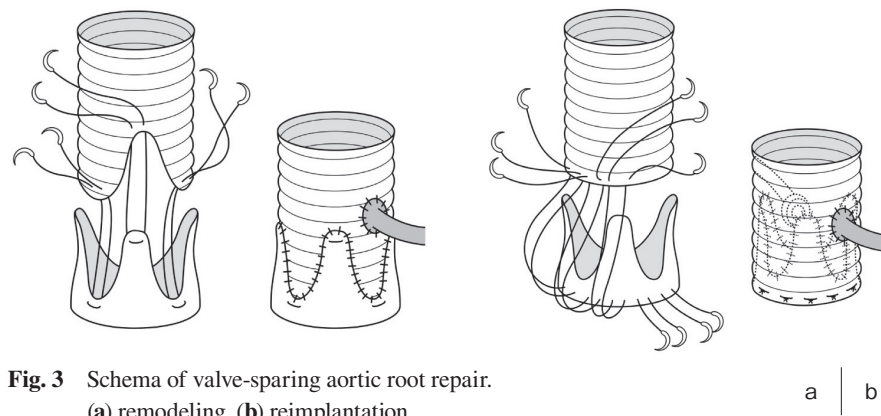


Fig. 3 Schema of valve-sparing aortic root repair. (a) remodeling, (b) reimplantation.

(**Fig. 3a**). Reimplantation is known as the David procedure in which a cylindrical graft is proximally sutured to the basal ring, and then the sinus remnant is sutured inside the aortic graft (**Fig. 3b**). Coronary ostia are reimplanted into the aortic prosthesis during both procedures in the same way as in the Bentall operation. One defining difference between the two procedures is the number of aortic suture lines, namely 2 (proximal, 1; distal, 1) rows in remodeling vs. 3 (proximal, 2; distal, 1) in reimplantation. Both VSRR techniques have achieved excellent early results but have pros and cons regarding aortic root physiology and aortic root support.

Remodeling is generally considered a more rapid and technically less complicated procedure. The advantages of remodeling are that a billowed graft mimics the natural sinus of Valsalva and that the absence of subannular sutures preserves some distensibility within the complex, asymmetric deformation of the normal aortic root during the cardiac cycle.¹⁵ These features allow more natural leaflet motion or less cusp-closure stress, and thus, theoretically, enhance the long-term durability of the valve. One drawback of remodeling is that the absence of subannular fixation can create a predisposition to postoperative annular dilation, resulting in recurrent AR. Another drawback is that two exposed aortic suture lines can result in a predisposition to bleeding.

On the other hand, reimplantation, where the basal ring is firmly anchored by the aortic prosthesis, has the advantage of preventing further dilation of the annulus. Another advantage is that the two rows of proximal suture lines provide more secure hemostasis, although Cameron and Vricella stitch only a few sutures at the basal ring,¹⁶ which is insufficient for hemostasis. The biggest disadvantage of reimplantation is the potential risk of impeding natural leaflet mobility in a rigid

straight graft.

Various VSRR Techniques

The VSRR technique is still under development, and the original procedure has undergone many improvements. Even David, who pioneered VSSR, has frequently changed his techniques. Miller numbered them for simplicity,¹⁷ and they are widely used (**Table 1**). The “David-I” procedure is the original reimplantation using a cylindrical tube graft. “David-II” is classic Yacoub remodeling. “David-III” is remodeling with an external synthetic strip added between the left and right mitral fibrous trigones [the fibrous portion of the left ventricular outflow tract, which is considered weaker than the muscular portion] to prevent further dilation of the annulus. Lansac and colleagues have recommended aortic prosthetic ring annuloplasty and have applied it as a systematic adjunct to the remodeling procedure.¹⁸ “David-IV” is reimplantation using a larger (4-mm) circumferentially plicated graft at the ST junction. Reducing the diameter of a dilated ST junction is important to restore aortic valve competence when patients have AR and normal aortic cusps.¹⁹ An even larger (diameter, 6–8 mm) graft is used in the David-V procedure, and it is necked down at both the bottom and the top ends to create graft pseudosinuses, because the sinuses of Valsalva are crucial for creating eddy blood flow for normal valve function. Although vortices cannot be visualized in the sinuses of Valsalva²⁰ and valve opening and closing dynamics are abnormally high in postoperative patients with negligible sinuses, near-normal valve opening and closing characteristics can be achieved by creating a sinus bulge.^{21, 22} Finite element analyses have demonstrated similar findings.^{23, 24}

Table 1 Procedural transition of valve-sparing aortic root repair

I	Reimplantation	Original
II	Remodeling	Original
III	Remodeling	with an external strip in the fibrous portion of basal ring
IV	Reimplantation	with plication of the graft at ST junction
V	Reimplantation	with plication of the graft at both the basal ring and ST junction to create the graft pseudosinus

ST junction, sinotubular junction

Many devices can create pseudosinuses. Svensson tied sutures over a Hegar dilator to reduce the basal ring to a mean normal diameter based on body surface area.^{25, 26)} Cochran and colleagues created pseudosinuses by the conduit modification of simply increasing the circumference by creating three symmetrical scallops in the base of the conduit where it is sutured to the basal ring.²⁷⁾ Demer and Miller used two differently sized prostheses,²⁸⁾ whereas, Takamoto and colleagues altered only one²⁹⁾ prosthesis to create pseudosinuses. De Paulis custom-designed an aortic root prosthesis resembling the form of the sinuses of Valsalva.³⁰⁾ This prosthesis saves many steps during the procedure and is now quite prevalent, although the size of the graft might not always be optimal. Cameron and colleagues have used this graft exclusively and found that all patients who underwent reimplantation using a Valsalva graft have no or mild AR.³¹⁾ De Paulis states that the rate of freedom from aortic valve reoperation at 10 years after VSRR using the Valsalva graft is 91%.³²⁾

Urbanski described another novel technique in which each pathological sinus is excised and replaced with a teardrop-shaped patch.³³⁾ Hess and colleagues developed the Florida sleeve, which is another less invasive approach.^{34, 35)} They place the aortic prosthesis like a sleeve over the aortic root and reattach the native aortic valve and coronary ostia, which can overcome most technical hurdles. Shrestha and colleagues applied a very similar technique to treat acute type A aortic dissection with acceptable results.³⁶⁾

VSRR Combined with Cusp Repair

The preferred modality to treat aortic root pathology even with AR is VSRR, providing that the leaflets are morphologically intact. However, the cause of AR is not always attributable only to aortic root dilation. Additional cusp repair would be necessary when a combination of cusp and root pathology is responsible for AR. Tech-

niques to correct cusp pathologies include free edge plication, free edge resuspension/reinforcement with Gore-Tex, triangular resection with a direct suture, patch insertion and others. Although significant preoperative AR or a need for cusp repair might be risk factors for poorer outcomes after VSRR,³⁷⁾ Schafers and colleagues have aggressively corrected leaflet prolapse surgically in combination with VSRR. They systematically corrected root dilation by remodeling, reimplantation, subcommissural plication or supracommissural aortic replacement and concomitantly corrected cusp prolapse by free edge plication or triangular resection. They found no differences in operative mortality, survival, and longevity of valve competence when a leaflet procedure was included.^{38, 39)} The Brussels group also demonstrated an acceptable mid-term outcome, irrespective of preoperative AR or the need for cusp repair. The predictors of recurrent AR were preoperative left ventricle end-diastolic diameter and residual AR on discharge echocardiography.^{40, 41)} These results might represent an earlier indication for VSRR and aggressive cusp repair if necessary. Svensson and colleagues used the CLASS (Commissure, Leaflet, Annulus, Sinuses, Sinotubular) evaluation for selecting the appropriate procedure and achieved excellent results after VSRR and concurrent cusp repair.⁴²⁾

Predictors of Recurrent AR after VSRR

The development of progressive AR can be influenced by cusp degeneration and by a deformed root geometry. The impact of extant AR^{37, 40, 41, 43, 44)} and the preoperative diameter of the aortic root^{45, 46)} are controversial. In theory, remodeling offers an advantage over reimplantation in terms of reduced cusp stress, whereas reimplantation confers an advantage in terms of annular fixation.

According to the latest report by David, the rate of freedom from moderate or severe AR is higher after reimplantation than remodeling (91.0% vs. 82.6% at 12 years; $p = 0.035$).⁴⁷⁾ A meta-analysis of the literature has

concluded that reimplantation is favored in terms of reconstruction longevity, particularly for treating congenital degenerative disorders of the aortic wall, whereas remodeling appears to result in a more physiological behavior of the reconstructed valve.⁴⁸⁾

As reimplantation using the Valsalva graft confers the advantages of less cusp stress and secure annular fixation, the reoperation rate should be lower.^{31, 40)} The level of cusp coaptation after reimplantation⁴⁴⁾ and residual AR upon discharge^{40, 41)} are possible predictors of recurrent AR. Whether VSRR combined with cusp repair is a risk factor for recurrent AR remains controversial.^{37–41)}

VSRR in Patients with Marfan Syndrome

Whether the Bentall procedure or VSRR should be the surgery of choice in Marfan syndrome is also controversial.^{49, 50)}

The Mayo group reported that the Bentall procedure generated a durable result with few serious complications related to a need for long-term anticoagulation or a prosthetic valve, although aortic valve failure after VSRR is a common cause of reoperation.¹¹⁾ However, the Toronto group reported that VSRR provides similar survival but lower rates of valve-related complications than the Bentall procedure for patients with Marfan syndrome.⁵¹⁾ The Hannover group has also used reimplantation exclusively for patients with Marfan syndrome with an excellent early outcome, favorable long-term results and acceptable durability of the re-implanted valve.⁵²⁾ The Madrid group reported excellent short- and mid-term results after reimplantation to treat aortic root aneurysms in patients with Marfan syndrome and concluded that if the long-term results are similar, then this technique could be the treatment of choice for such patients.⁵³⁾

According to a recent study by the Johns Hopkins group who had reported excellent early and long-term results after the Bentall operation,⁵⁴⁾ Bentall and VSRR result in similar operative outcomes in Marfan syndrome. Although rates of thromboembolism and reoperation are higher after the Bentall procedure and after VSRR respectively, propensity score-adjusted Cox regression analysis revealed that the Bentall procedure neither predicts late mortality nor protects against a need for reoperation.⁵⁵⁾ The largest and most recent study of 372 Marfan patients concluded that VSRR is promising, particularly when using reimplantation with a Valsalva graft, but it has not yet proven as durable as the Bentall procedure.³¹⁾

VSRR in Patients with Bicuspid Aortic Valve

A bicuspid aortic valve (BAV) is associated with aortic dilation in over 50% of patients.⁵⁶⁾ Borger and colleagues recommended that concomitant replacement of the ascending aorta should be considered for patients undergoing surgery to treat BAV if the diameter is ≥ 4.5 cm.⁵⁷⁾ Although whether repair has real advantages over early aortic valve replacement has not been confirmed, Veldtman reported that repairing a diseased BAV during VARR is safe and results in good early functionality.⁵⁸⁾ Schafers emphasized that symmetric cusp prolapse might be induced by any operation that reduces the diameter of the ST junction, and this must be corrected to avoid AR recurrence.⁵⁹⁾ David recommended reimplantation as the procedure of choice, because further dilation of the aortic root is a common postoperative cause of recurrent AR in patients with BAV.⁶⁰⁾

VSRR in High-risk Patients

The indications for VSRR are increasing. Some surgeons have considered that high-risk patients with acute type A dissection,³⁶⁾ reoperation for severe AR⁶¹⁾ and advanced age⁶²⁾ are also possible candidates for VSRR. However, the population of each study was too small, and the observation period was too short to verify the effectiveness of VSRR in each subcategory. The outcomes of high-risk patients require further observation.

Conclusions

Valve-sparing aortic root replacement is an attractive option for treating aortic root pathology, especially in young patients. A precise understanding of the anatomy and function of the aortic root-valve complex is essential for the success of these technically demanding procedures. Despite excellent early and mid-term results, these procedures can be further improved. Appropriate patients and procedures should be selected based on data from larger studies with a longer follow-up.

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