Surgical Approaches to Aortic Valve Replacement and Repair—Insights and Challenges

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Abstract
Since 1960, surgical aortic valve replacement (sAVR) had been the only effective treatment for symptomatic severe aortic stenosis until the recent development of transcatheter aortic valve replacement (TAVR). TAVR has offered an alternative, minimally invasive treatment approach particularly for patients whose age or co-morbidities make them unsuitable for sAVR. The rapid and enthusiastic utilization of this new technique has triggered some speculation about the imminent demise of sAVR. We believe that despite the recent advances in TAVR, surgical approach to aortic valve replacement has continued to develop and will continue to be highly relevant in the future. This article will discuss the recent developments and current approaches for sAVR, and how these approaches will keep pace with catheter-based technologies.

Keywords
Aortic stenosis, surgical aortic valve replacement (sAVR), mini thoracotomy, mini sternotomy, aortic regurgitation

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Symptomatic severe aortic stenosis or insufficiency have no effective medical treatments and carry a dismal prognosis if left untreated. Since the first aortic valve replacement in 1960, hundreds of thousands of lives have been saved and improved by this procedure. Until recently, surgical aortic valve replacement (sAVR) was the only effective therapy for severe aortic valve stenosis. The recent introduction of transcatheter aortic valve replacement (TAVR) has offered an alternative in specific high-risk patients with symptomatic severe aortic stenosis. The rapid adoption and dissemination of TAVR have led some to speculate on the demise of sAVR. Although TAVR has and will continue to cater to a portion of patients with aortic valve disease, in the meantime, the field of sAVR has not stood stagnant but rather continues to advance and improve in tandem with TAVR. In addition to surgical valve replacement techniques, repair principles have been adopted from the mitral valve to the aortic valve with growing success leading to the standardization of regurgitant aortic valve repair approaches. This article will examine the current surgical approaches for aortic valve replacement with insights into the challenges faced and how these approaches will remain competitive with catheter-based technologies. We will focus on minimally invasive approaches to sAVR, new valve technologies, and aortic valve repair techniques.

Minimally Invasive Surgical Aortic Valve Replacement
sAVR requires the use of the heart lung machine to stop the heart and to allow access to the aortic valve within the heart. The traditional approach to exposing the heart for bypass and to gain access to the aortic valve has been via median sternotomy. Median sternotomy allows excellent access to all cardiac structures but requires complete division of the sternum and sternal spreading. This disrupts the integrity of the chest wall in the early recovery phase. Surgeons therefore decided to look for less invasive ways of performing sAVR to see if this would lead to easy recovery and possibly improved results for patients. The parasternal approach to sAVR was first reported by Cosgrove in 1996, but has been largely abandoned due to chest wall hernias.[1] The right mini thoracotomy approach was introduced by Benetti in 1997[2] and the mini sternotomy approach by Gundry in 1998.[3] At the Houston Methodist Hospital, we began our minimally invasive valve program in 1999 when we performed anatomic studies on cadavers. In these studies, we examined the relationship of the cardiac valve structures to the chest wall to help plan potential surgical approaches.[4] From these early studies in our program, we have employed two minimally invasive approaches to sAVR: mini sternotomy and mini thoracotomy (see *Figure 1*).

Right Anterior Mini Thoracotomy
Right anterior mini thoracotomy is performed with the patient in the supine position with femoral cannulation, most commonly for both the venous and arterial cannulae. In cases where retrograde aortic blood flow is not desired (e.g. peripheral vascular disease), direct cannulation of the distal ascending aorta or right axillary can be performed along with percutaneous femoral venous cannulation. An incision is made over the right third intercostal space and the fourth

costal cartilage is divided to allow exposure. Cardioplegia can be performed by direct antegrade coronary infusion through the aortic root or a retrograde coronary sinus catheter can be placed via the right jugular vein under transesophageal echocardiographic (TEE) and/or fluoroscopic guidance. It is also possible for the surgeon to place a retrograde catheter directly through the right atrium with echo guidance. A malleable aortic clamp is used for cross-clamping the aorta and aortotomy exposure is standard. Left ventricular vent (right superior pulmonary vein [RSPV]), replacement of the aortic valve, and suture placement is similar to standard sternotomy approach. Care must be taken to ensure the far corner of the aortotomy closure is secure before coming off cardiopulmonary bypass (CPB), as this area can be difficult to see in some patients after separation from bypass. The advantage of this approach is that it does not destabilize the sternum and the chest wall. Disadvantages can include occasional decreased exposure and the need to divide the right mammary artery in all cases. A preoperative chest computed tomography (CT) scan can be helpful for preoperative planning and delineation of aortic anatomy/orientation.

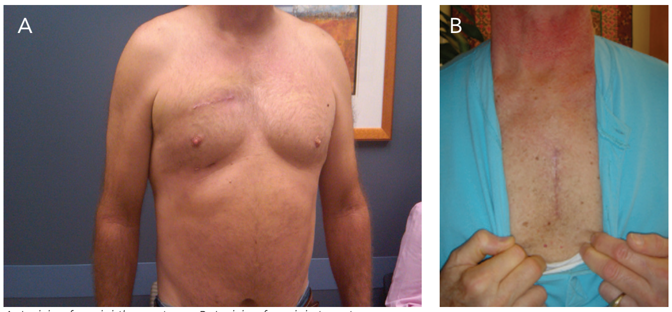
Mini Sternotomy

Mini sternotomy is carried out with the patient supine. A skin incision is made over the upper sternum. The third or fourth right intercostal space is exposed and opened next to the sternum. The sternum is divided from the sternal notch to this level and then 'Jed' off into the right interspace. Cannulation for bypass can be performed completely centrally or, more commonly, we use percutaneous femoral venous drainage and central aortic arterial return. This affords excellent exposure of the ascending aorta and aortic root similar to full sternotomy. Cardioplegia can be administered via direct antegrade infusion through the aortic root or combined with retrograde infusion via the coronary sinus. We can generally cannulate the coronary sinus under TEE guidance through the right atrium and the RSPV can be used to decompress the left ventricle. Both mini thoracotomy and mini sternotomy offer limited access, which can complicate de-airing, therefore, we use CO_2 insufflation. The advantage of the sternotomy approach is that it is familiar to more cardiac surgeons who are used to full median sternotomy, affords excellent exposure of the ascending aorta and aortic root, can be used with central cannulation, does not violate the pleural space, and is easily converted into a full sternotomy if needed. The fact that part of the sternum is divided is considered by some to be a disadvantage of this approach.

Outcomes for Minimally Invasive Surgical Aortic Valve Replacement

For minimally invasive sAVR to be successful, it should, at a minimum, pose no safety hazards and allow the same technical valve procedure as full sternotomy AVR. Additionally, it would be hoped that these approaches would improve mortality, morbidity, and cause less pain and faster recovery. A number of observation studies of minimally invasive sAVR have shown less blood loss and blood usage, shorter hospital stays, less atrial fibrillation, and faster return to functional activity.[5–7] Propensity matched studies of minimally invasive versus full sternotomy sAVR have confirmed the safety of these approaches, but have not shown a survival advantage in average risk patients.[8–10] The safety of this approach has even been shown in reoperative sAVR,[11] the elderly,[12] and high-risk patients.[13] Small randomized studies have also started to appear in the literature.[14] The overall consensus is that a minimal approach provides the same safety as the conventional

Figure 1: Placement of Incision for Mini Thoracotomy and Mini Sternotomy



A. Incision for mini thoracotomy. B. Incision for mini sternotomy.

Figure 2: Trifecta Pericardial Valve

approach, and offers some advantages including less blood loss, shorter hospital stay, faster recovery in the early phase, and better patient acceptance.

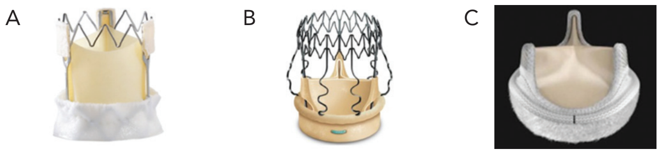
Valves

Currently, two main groups of artificial valves or prosthesis are available for aortic valve replacement. These are mechanical valves and tissue/bioprosthetic valves. The main advantage of mechanical valves is their excellent durability. Their principal disadvantage is the need for lifelong anticoagulation therapy due to increased risk for blood clots. Tissue valves, on the other hand, have less durability and tend to wear out sooner than mechanical valves. However, they do not require lifelong anticoagulation. Over the last 2 decades, there has been a growing trend to implant more tissue aortic valves as opposed to mechanical valves.[15] Tissue aortic valves (e.g. bovine, porcine, and homografts/human cadaveric aortic valves) can be stented or stentless. One major concern with stented (tissue mounted on a stent) bioprosthesis has been the less-than-optimal systolic hemodynamic performance with the smaller sizes. Stentless bioprosthesis have excellent hemodynamics but are generally more complex to implant in the subcoronary position or are carried out as a root replacement, which is a longer and more complex procedure. In this review, we will focus on the more commonly used stented bioprosthesis. TAVR series have shown excellent systolic hemodynamic function in all annular sizes thus presenting a challenge for sAVR using stented bioprosthesis.[16,17] Valve innovation is fortunately still occurring and one answer to improving the systolic hemodynamics of the stented bioprosthesis is the new St Jude Medical Trifecta valve (St Paul, Minnesota, US).

The Trifecta valve is an externally wrapped, stented pericardial valve designed to allow a larger effective orifice area (EOA) (see *Figure 2*). A clinical trial with this valve was conducted from 2007 to 2009 at 31 centers and published in 2014.[18] The question of poor hemodynamic performance in the smaller sizes did not appear in this series. All valves

Figure 3: McGovern-Cromie Valve

Figure 4: New Sutureless Aortic Valves



A. Enable valve. B. Perceval S valve. C. Intuity valve.

from 19 mm to 29 mm had single digit mean gradients at discharge. At 1 year, this still held true for all but the 19 mm size, which had a mean gradient of 10.7 mm Hg, which is still highly desirable. Mean indexed EOA at 1 month did not show any patient prosthetic mismatch (PPM) and only the 19 mm size gave an indexed EOA of 0.85 cm^2/m^2, which is the absolute upper end of moderate PPM. Early results with the Trifecta valve are promising, with indications of improved systolic hemodynamics and potential advantages of lower transvalvular gradients. However we would like to point out that, currently, this is one of the several options available and that longer term follow-up data are necessary to evaluate the effectiveness and durability of this design. Further, if this valve does undergo structural valve deterioration necessitating a new valve, the external pericardial wrap may make coronary occlusion a greater risk if the TAVR valve-in-valve method is chosen and this remains to be tested.

Sutureless Valves

The concept of an aortic valve that could be placed without sutures is not new and in fact originated with the McGovern-Cromie valve in 1964 (see *Figure 3*). The success of TAVR has refocused attention in this area and currently three sutureless aortic valves are either available outside of the US or being tested here (see *Figure 4*). The 3f Enable bioprosthesis by Medtronic (Medtronic, Inc., Minneapolis, Minnesota, US) and the Perceval S by Sorin (Sorin Biomedica Cardio Srl, Saluggia, Italy) are self-expanding with Nitinol frames and pericardial leaflets. The Intuity by Edwards (Edwards Lifesciences, Irvine, California, US) has a balloon-expandable frame and pericardial leaflets. Although termed sutureless valves, guiding sutures are often used to seat the valve properly and a better term for them might be rapid deployment valves. These valves are placed when the patient is on CPB with aortic cross-clamp (ACC) under cardioplegic arrest. The native stenotic leaflets are removed, but without the meticulous decalcification normally carried out for a sAVR, as some remaining calcium will help hold the valve in place. The concept for these valves is that they would simplify valve implantation by shortening both cross-clamp time and cardiopulmonary bypass times and maintain the excellent hemodynamics seen in TAVR, but with a decreased incidence of paravalvular leak (PVL), and thus will allow increased adoption of minimally invasive surgical approaches to sAVR. Shortening cross-clamp and CBP times is appealing in terms of reducing operative time and because these are known to carry the risk for postoperative mortality and morbidity, especially in higher risk patients, or when combined procedures need to be performed (AVR/coronary artery bypass surgery [CABG] or multiple valves).[19]

Sutureless aortic valves are still early in their development and a number of smaller trials with these exist. One of the larger trials was reported by Kocher and involved 146 patients in six European centers using the Intuity valve.[20] The 1-year hemodynamic performance was good but two early and two late valve explants were required. The ACC time was 41.1 minutes and only 31.1 % of the cases were performed via a minimally invasive approach. A propensity matched study between 519 patients having TAVR or sAVR using the Perceval S valve and then matched to 38 pairs has been presented by D'Onofrio.[21] Hemodynamic performance, complications, and pacemaker insertion rates were similar between the groups. Differences were seen in a greater rate of atrial fibrillation in the sAVR group (42 % versus 16 %) and a lesser rate of at least mild PVL in the sAVR group (16 % versus 45 %), though PVL results along the same lines may not be representative of all studies. Current data on sutureless aortic valves would suggest that they can be used safely, with good hemodynamics and with acceptable complication rates. It is however unknown if this will increase the adoption of minimally invasive approaches to sAVR or improve patient outcomes. Also unknown is the long-term durability of these valves. Despite these areas of concern, these valves offer the potential for a simplified and reproducible technique for sAVR, provide another tool in the toolbox of aortic surgeons, and deserve further study.

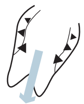
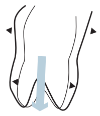
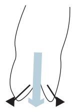
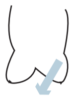
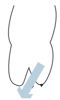
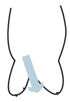
Aortic Valve Repair

The success of mitral valve repair in treating mitral regurgitation has prompted the development of repair techniques for aortic regurgitation. Successful aortic valve repair as opposed to sAVR would allow the patient to avoid anticoagulation as well as structural valve deterioration. Successful aortic valve repair, like mitral valve repair, requires an understanding of the mechanisms leading to aortic insufficiency (AI). A functional classification of AI similar to the Carpentier classification for mitral regurgitation has been presented by El Khoury[22] (see *Figure 5*). Type I AI shows central regurgitation. This can occur from dilatation of the annulus or the sinotubular junction. Dilatation of the sinuses alone does not lead to AI. Additionally a perforation of the valve cusp can lead to a Type I central regurgitation. An eccentric regurgitation from cusp prolapse is seen in Type II and from cusp restriction in Type III. Repair techniques, as with mitral valve repair, are dependent on the mechanism causing the regurgitation.

Type I Aortic Regurgitation

Central regurgitation due to cusp perforation can occur in endocarditis or trauma. If the regurgitation is limited, it can be repaired by pericardial patch closure. The more common causes of Type I AI are annular and sinotubular junction dilatation. Occasionally, the AI is due to dilatation of the sinotubular junction when an ascending aortic aneurysm is the only pathology. The aortic aneurysm can be repaired by graft replacement of the ascending aorta. The diameter of the graph is equal to the free margin (annular diameter) of the cusps or slightly undersized. This brings the commissural posts back into alignment and allows proper coaptation of the valve cusps to eliminate AI. Annular dilatation requires reducing the annular diameter. Although there are subannular rings being developed for this purpose similar to mitral rings, they are still early in their development. This is more commonly performed using a valve sparing

Figure 5: Functional Classification of Aortic Insufficiency

AI Class	Type I				Type II	Type III
	Normal cusp motion with FAA dilatation or cusp perforation					
	Ia	Ib	Ic	Id	Cusp Prolapse	Cusp Restriction
Mechanism						
Repair Techniques (Primary)	STJ Remodeling Ascending aortic graft	Aortic Valve Sparing Reimplantation or remodeling with SCA	SCA	Patch Repair Autologous or bovine pericardium	Prolapse Repair Plication Triangular resection Free margin Resuspension Patch	Leaflet Repair Shaving Decalcification patch
(Secondary)	SCA		STJ Annuloplasty	SCA	SCA	SCA

AI = aortic insufficiency; FAA = functional aortic annulus; SCA = subcommissural annuloplasty; STJ = sinotubular junction. Source: Boodhwani M et al., 2009.[29] Reprinted with permission.

root replacement (VSRR) technique. Two common approaches have been used for fixing annular dilatation: remodeling introduced by Sarsam et al.[23] and the reimplantation technique introduced by David et al.[24] (see *Figure 6*) The remodeling technique removes the sinuses and coronaries are freed up as buttons, leaving the aortic valve and a several millimeter rim of sinus above the annulus. A graft is then fashioned with tongues that extend down to replace the sinuses and the coronary buttons are then reimplanted. The reimplantation technique differs in that the graft is brought over the remaining valve and rim of the sinus tissue. The graft is loosely sewn with subannular sutures extending out through the graft to hold it in place. The valve complex is then sewn inside the graft forming the hemostatic sealing suture line. The coronaries are then reimplanted in a standard fashion. The reimplantation technique allows stabilization of the annulus unlike remodeling. Reimplantation may potentially be a better approach for a patient subject to recurring annular dilatation like patients with connective tissue disorders or bicuspid valves.

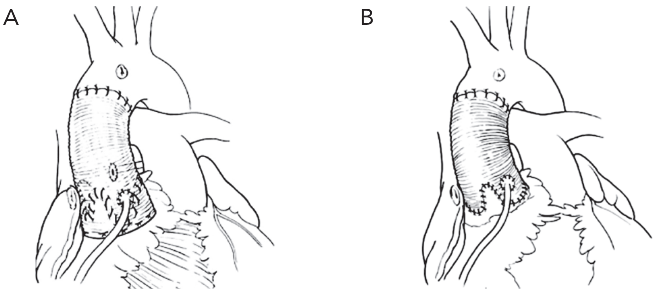
Type II Aortic Regurgitation

Cusp prolapse may occur with Type I anatomy or in isolation. The base of the valve cusp is generally about 1.5 times longer than the free margin of the cusp. If the free margin elongates and approaches the length of the base, then the cusp will prolapse into the ventricle during diastole and allow AI. The surgical solution to this is to shorten the free margin length of the cusp. This can be performed by resection of the center point of the elongated cusp or just suture imbrication of this area. The cusps can also be shortened by imbrication at the aortic wall or by placing a free margin suture of fine polytetrafluoroethylene (PTFE).

Type III Aortic Regurgitation

Like restricted leaflets in mitral regurgitation, cuspal restriction in AI does not lend itself well to repair using current techniques and generally requires valve replacement.

Figure 6: Valve Sparing Root Replacement Techniques



A. Diagrammatic representation of reimplantation. B. Diagrammatic representation of remodeling. Both figures reprinted with permission. Source: David TE, Korean J Thoracic Cardiovasc Surg, *2012;45:207 (Figure B); 208 (Figure A).*

Outcomes for Aortic Valve Repair and Valve Sparing Aortic Root Procedures

Long-term results have been reported for several studies that have used the remodeling or reimplantation approach. Following remodeling, freedom from moderate or severe AI at 10 years was 64 % in the study by Yacoub et al.,[25] 96 % for bicuspid valves, and 87 % for tricuspid valves as reported by Aicher et al.[26] Following reimplantation, freedom from reoperation at 10 years was 93 % for David et al.[27] and 88 % for De Paulis et al.[28] Aortic valve sparing operations have been shown to have good long-term outcomes in experienced centers and offer the ability to maintain the patient's native valve.

Conclusion

Surgical approaches to aortic valve disease continue to advance and improve. We agree that TAVR technology is an exciting and useful addition to the surgeon's toolkit for treating aortic valve disease but also believe that surgical improvements will keep sAVR highly relevant and necessary for a large portion of patients with specific aortic valve pathologies. ■

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