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REVIEW

Aortic Valve Repair: Where Are We Now?

Lara Rimmer, MBBS [a], Mohammad U. Ahmad, MBBS [b], Grace Chaplin [c], Mihika Joshi, MBBS [d], Amer Harky, MBChB, MSc, MRCS [e*]

[a]East Lancashire Hospitals Trust, Blackburn, UK
[b]Department of Surgery, Scunthorpe General Hospital, Scunthorpe, UK
[c]School of Medicine, University of Liverpool, Liverpool, UK
[d]Department of Vascular Surgery, Countess of Chester, Chester, UK
[e]Department of Cardiothoracic Surgery, Liverpool Heart and Chest Hospital, Liverpool, UK

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The advent of aortic valve repair alongside the well-established technique of valve replacement changed the landscape of cardiac surgery, as well as the lives of patients suffering from valvular disease. Repair represents a novel option in those unfit for replacement and avoids the burden of lifelong anticoagulation in younger patients. Despite this, the associated risk of persistence of aortic insufficiency, and therefore reoperation, with valvular repair renders clinical decision making between the two techniques difficult. Unlike the burden of evidence supporting mitral valve repair over replacement, the debate surrounding aortic valve surgery continues.

This article aims to explore the development of operative techniques underlying aortic valve repair as well as summarising existing research into short- and long-term patient outcomes in both aortic valve repair and replacement.

Keywords Aortic valve • Repair • Valve surgery • Aorta

Introduction

The aortic root is a complex unit consisting of streamlined segments [1]. The aortic sinuses, the cusps, annulus and the commissures all act together to allow the valve to properly function [1]. The aortic root is responsible for the left ventricular outflow tract and thus maintaining laminar flow [2]. Diseases of the aorta, such as dissection or aneurysm, can alter the flow through the valve or alter the valve morphology and functions themselves [2]. Valves can undergo a number of transformations, such as deformation, stretching, calcification, dilatation or even rupture. This can lead to either aortic stenosis (AS) or insufficiency (AI), which could stay asymptomatic over long periods of time or present acutely [3]. AI has recently been classified according to the mechanisms of its occurrence [3,4]. The most historical treatment of this is to replace the valve using a mechanical or biological valve either isolated or replaced with another part of the aorta [5,6]. The disease process of aortic regurgitation secondary to aneurysm or dissection of the aorta may be isolated to damage to the aortic wall, and the valve may be intact. At first, this meant the valve had to be entirely normal, but current techniques can repair prolapsing, fenestrated or flimsy valves [7].

Repairing the aortic valve is beneficial in certain groups of patients, such as children, who have limited options for replacement [8,9]. There are also coagulation ramifications for valve replacement as lifelong anticoagulation is required for risk of thromboembolism [5]. Concerns regarding aortic valve repair are related to its surgical technique; further requirements to repair the valve, or the decision to replace it, carries a risk of reoperation [5,10]. The valve can develop or continue to have AI [2]. Therefore, the choice between the two is not always clear.

The decision of whether to use aortic valve replacement (AVR) or aortic valve repair (AVr) began in the mid-nineteenth century and the debate continues until today. The decision remains to treat the patient with an appropriate technique on a case-by-case basis, using surgical anatomy as well as patient comorbidities to guide the surgeon's

*Corresponding author. Email: aaharky@gmail.com

decision [9]. This article will outline the history of the development of AVr, the groups that benefit, the operative techniques and the short and long-term outcomes. Table 1 is summary of the key papers in literature about AVr and their reported outcomes.

History of Aortic Valve Repair

"It is good for you to argue about what will happen under certain conditions, but do not let these arguments prevent you trying to find out by practical experience what the answer is."[11].

Many nuances in the history of cardiac surgery have been lost to time, but the key players of the mid-nineteenth century shaped the treatment of aortic valve repair we know today.

With rheumatic fever (RF) and congenital disease being the main causes of valve dysfunction and death, prior to 1942, antibiotic treatment surgeons were faced with severely ill young patients with thickened and stenosed valves [12]. Commissurotomy, a technique to dilate a stenosed valve manually by inserting a finger, was used originally on the stenosed mitral valve by Charles P. Bailey [13,14].

World War II brought about many collaborations, but also the development of surgeries previously unheard of. Dwight Harken performed the first valvuloplasty after 142 successful operations to remove missiles and shrapnel from in and around the hearts of soldiers [15,16]. In 1946, Alfred Blalock's work creating Blalock-Thomas-Taussig shunt brought him into contact with Maurice Campbell, editor of *Heart*, and they worked together to perform a valvotomy [11,17,18].

Charles Hufnagel advanced valve sparing surgery with the introduction of a design of a sutureless valve of a plastic tube filled with a ball; intended to regulate blood flow without needing to replace or repair the valve [19,20].

In 1953, the first heart lung bypass machine was used successfully by Gibbon, and valve replacement used similar designs to Hufnagel—the Starr-Edwards valve—with longer operative times for instalment [6,21]. These successful replacement operations paused much of the development of valve repair [13,22,23]. In 1989, Tirone David performed the first valve sparing operation in the face of normal aortic cusps [7]. In 1996, Charles D Fraser and Delos Cosgrove reignited their use of valve repair for young patients in their paper, which remarked that essential to successful repair is to delineate initially the cause of the fault—which still stands today [24].

Who Needs Aortic Valve Repair?

Aortic valve repair became the increasingly preferred choice of management for patients with limited options of repair or those who may find difficulties in anticoagulation due to the risk of thromboembolism [8,9]. The aim of AVr may not be to restore normal anatomy within the patient but to restore normal function of the valve [25]. Whilst there may be subtle differences in patient selection for AVr and AVR, the patients selected for AVr will still be generically similar to those who are selected for AVR [26].

The first group of patients that are increasingly being selected for repair and not replacement is children. Children have limited options for replacement due to their anticipated growth and the need for repeated operations if they were to undergo replacement [27]. The constant requirement for anticoagulation and risks associated with this, lack of activity restriction, compliance with medical regimens as well as high risk behaviour make the prospect as valve replacement in children a daunting one [27]. If patients can undergo repair with satisfactory postoperative and long-term results, then this is a viable alternative to aortic valve replacement. Increasingly over the past 20 years, there has been a wider acceptance of AVr in children as opposed to AVR [9].

There is a large number of adult patient groups which are also fit for AVr and not replacement. The selection criteria is based on a number of different factors including and not limited to symptoms of the patient, concomitant procedures, degree of aortic insufficiency or aortic regurgitation, left ventricular (LV) systolic function and surgical risk of operation [26]. AVr is recommended for patients who have severe regurgitation regardless of LV systolic dysfunction or those undergoing concomitant cardiac procedures; AVr is also reasonable in those patients with moderate insufficiency and undergoing concomitant procedures [26]. AVr is reasonable in the following asymptomatic patient groups: chronic severe aortic insufficiency with LV systolic dysfunction ((left ventricular ejection fraction) LVEF $<$ 50%); severe aortic insufficiency with normal LV systolic function, but with severe LV dilatation ((left ventricular end diastolic diameter) LVEDD $>$ 50 mm); severe insufficiency and normal LV systolic function but with progressive severe LV dilatation (LVEDD $>$ 65 mm) if the surgical risk is low [26,28,29].

In addition to the above, there have been several studies exploring the utilisation of AVr in patients with type A aortic dissection through valve sparing aortic root repairs. This lethal condition can present with varying degrees of aortic valve insufficiency and this could be due to either annular dilatation, commissural disruption or impingement of the valve cusps with the dissection flap [29]. The choice of repairing or replacing the aortic valve remains difficult and complex. Particularly in young patients, where a life-long anticoagulation is required to prevent thrombo-embolic events. Additional to risks of thrombo-embolism vs bleeding in such a cohort, re-intervention rate for replacing the aortic valve at later stage is another detrimental factor [28]. Furthermore, surgeon experience is another point to consider when repairing the valve, as a less experienced surgeon likely will replace the valve rather than repair it.

In a recent systematic review and meta-analysis of 2,402 patients of acute type A aortic dissection that underwent AVr, the authors noted that there is a significant rate of re-intervention (2.1% per patient/year) and recurrence of moderate to severe aortic regurgitation was 1% per patient/year

Table 1 Outcome summary data for 11 papers on aortic valve repair.

Name (Ref)	Year	Study Type	Sample Size	Patient Population	Outcome measures	Results	Overall Conclusions
Aicher D et al. [51]	2010	Retrospective	640	Patients undergoing AV reconstruction for regurgitation; comparing those with isolated valve repairs with those undergoing replacement ± concomitant cardiac procedures.	Hospital mortality, thromboembolism, endocarditis, freedom from reoperation	• Those undergoing isolated repairs (0.8%) compared to the remaining cohort (3.4%) and more complex concomitant cardiac surgery (8.1%) showed a lower mortality. Freedom from valve-related complications was 88%.	Repair is feasible with a low mortality, and freedom from valve related complications is superior to existing data on valve replacement.
Aicher D, Kunihara T. [36]	2011	Retrospective	316	Patients undergoing reconstruction for regurgitant bicuspid aortic valves.	Hospital mortality, overall survival and freedom from reoperation	• Operative predictors for reoperation were age <40 years and higher degree of preoperative AR. • In hospital mortality was 0.63%, 99% at 5 years. Freedom from reoperation at 5 years was 88%.	Reconstructing bicuspid aortic valves occurred with positive early results. It was however found that recurrence and progression of AR can occur later on especially with reference to the underlying valvular anatomy.
Ashikhmina et al. [64]	2010	Retrospective	108	Patients >18 years undergoing bicuspid aortic valve repair for AR compared to age- sex-matched cohort who had replacement	Overall survival and freedom from reoperation	• 5 and 10 year survival rates 96% and 87%, showing no significant difference compared to matched bioprosthesis cohort ($p = 0.13$) • Freedom from reoperation 96%, 89% and 49% at 1, 5 and 10 years ($p < 0.12$)	No significant difference in the matched patients in terms of survival nor freedom from operation.
Badiu et al. [65]	2011	Prospective	100	AV repair patients for bicuspid and tricuspid AV insufficiency	Overall survival, freedom from reoperation and recurrent AR.	• Overall 3-year survival was 93 + 4.2% without significant difference between groups ($p = 0.59$). • Freedom from reoperation 86 ± 5.1% again without significant difference ($p = 0.98$).	There was no significant difference between bicuspid and tricuspid anatomy patients in those undergoing aortic valve repair in terms of survival and freedom from reoperation. This paper advocates repair of insufficient bicuspids.
Boodhwani et al. [66]	2011	Prospective	428	Patients undergoing aortic valve repair in isolated group	Freedom from reoperation, freedom from recurrent AI.	• Freedom from reoperation at 8 years was 100% in isolated	Recognising isolation of aortic cusp prolapse

Table 1. **(continued).**

Name (Ref)	Year	Study Type	Sample Size	Patient Population	Outcome measures	Results	Overall Conclusions
				(cusp disease) vs associated group (aortic dilatation)		and 93 + 5% in associated (p = 0.33). • Freedom from AI at 5 years 90 + 5% in isolated and 85 ± 8% in associated (p = 0.54).	preoperatively makes an impact on outcomes of valve sparing procedures.
Fattouch et al. [54]	2012	Prospective	216	Patients with AI undergoing aortic valve repair, with some undergoing concomitant aortic replacement procedures (68%)	Late incidence of recurrent AI, freedom from cardiac related death and valve related events.	• 6 (2.7%) overall in hospital deaths • Overall survival rate 91.5% • 14.5% had recurrent moderate or greater AI • Predictors for this were bicuspid type 2 A V (p = 0.0003), Type III dysfunction (p = 0.001), free-edge reinforcement (p = 0.01), and isolated AVR (p = 0.01)	Isolated repair produced worse results when compared to concomitant AVR and aortic procedures.
Fok et al. [45]	2014	Systematic review	4986	Adults undergoing aortic valve repair; some bicuspid repair, some cusp prolapse and others with aortic root surgery.	In hospital mortality, reoperation for valve failure, AI at discharge.	• Mortality for all studies 1.46 ± 1.21% • AI at discharge in 6.1% of patients • Reoperation following cusp prolapse repair = 3.83 ± 1.96% • Reoperation following bicuspid repair 10.23 ± 3.2% • Reoperation with aortic concomitant procedures was 4.25 ± 2.46%	''Absence of compelling supporting evidence'' for aortic valve repair compared to replacement.
Kerchove et al. [4]	2008	Prospective	146	Elective AV repair for one or more leaflet prolapses.	In hospital mortality, reoperation, overall survival.	• No in hospital mortality • 99 ± 1% overall survival at 4 years. • Freedom from reoperation = 94 ± 5% • Freedom from recurrent AI = 91 ± 7% • More leaflet prolapses did not affect recurrent AI (p = 0.2)	Multiple over single leaf prolapse is not prohibitive in a successful aortic valve repair.

Table 1. (continued).

Name (Ref)	Year	Study Type	Sample Size	Patient Population	Outcome measures	Results	Overall Conclusions
Lansac et al. [67]	2010	Prospective	187	Patients with dystrophic root aneurysms undergoing cusp repair using different methods. Group 1: gross visual estimation, Group 2: alignment of cusp free edges and group 3, a 2-step alignment of cusp free edges and height resuspension.	In hospital mortality, reoperation	• Operative mortality rate 3.2% • 9 patients required reoperation in 2 years • At 1 year, 28.1% of Group 1 patients and 15% of Group 2 patients had composie outcome events; there were none in Group 3 ($p < 0.001$).	A standardised approach to repairing the valve using root remodelling and resuspension of the cusp may aid results.
Minakata et al. [68]	2003	Retrospective	160	Patients undergoing aortic valve repair categorised according to cause of disease (bicuspid valve, dilatation, prolapse)	In hospital mortality, reoperation, overall survival.	• In hospital mortality n = 1 (0.6%) • 4 year mortality n = 16 • Risk of reoperation 9% at 3 years and 11% at 5 years. • Late recurrence of AI led to reoperation in 8.8%	Repair is a good option for young patients who wish to avoid lifelong anticoagulation, and can be performed with low risk.
Price et al. [50]	2012	Prospective	475	Patients undergoing elective AV repair for AI or root aneurysm.	30-day mortality, freedom from cardiac death or further AI, overall survival, reoperation rates.	• 30 day mortality = 0.8% • Overall survival at 10 years = 73 ± 5% • Freedom from cardiac death = 81 ± 4% • Freedom from AI 84 ± 3%; no difference between bicuspid and tricuspid valves ($p = 0.6$), nor existence of preoperative AI ($p = 0.2$). • Early (n = 7) and late (n = 21) reoperation was required in some patients, with no difference between bicuspid or tricuspid valves ($p = 0.8$) or preoperative AI ($p = 0.08$) • 10 year freedom from AV reoperation = 86 ± 3%	Repair of the aortic valve is associated with a low mortality and conveys a low risk of requiring further reoperation for additional valvular events.

Abbreviations: AV, aortic valve; AR, aortic regurgitation; AI, aortic insufficiency.

[29]. This study shows that choice of aortic valve repair must be done very carefully in such high-risk cohort patients.

Whilst there are various factors which may impact a patient's selection for AVr, it is important that these are considered with the evidence and the best choice for the patient in the long term.

Surgical Approach

Objective of AVr Surgical Techniques

There are varying techniques that are used by different surgeons all over the world. However, regardless of the surgical approach or technique, the first important point to note is that the technique must address the cause of the aortic pathology. As discussed previously, the aim of the operation is not to restore normal anatomy only, but to restore normal valve function within the patient. After considering the different types of patient populations to undergo AVr and the different indications for the intervention, it is important to consider the areas which can be reconstructed to achieve the aim of normal valve function. There are four main areas that can be addressed for the surgeon's intervention: the aortic annulus, aortic valve leaflets, aortic sinus and the sinotubular junction. All of the aforementioned areas will influence and have some impact on each other. A sound and well-informed understanding of these different areas, their role in normal physiology and an appreciation of how to influence and use the different areas are key to selecting a good strategy for AVr. After analysis of these different areas, a strategy for intervention can be planned. The strategy could mean intervention of the valve (aortic annulus or aortic valve leaflets), outside the valve, or intervention of both the ascending aorta and the aortic valve [30–32]. Figure 3 illustrates the stages and type of aortic valve repair techniques.

Principles of AVr Techniques

Understanding the following will help to explain the techniques of AVr. At the proximal aorto-ventricular junction and distally at the sinotubular junction the aortic valve leaflets inset into the aortic annulus. In normal aortic valve anatomy, the cusps fasten centrally to the aortic valve orifice with the height approximately at the midlevel of the aorto-ventricular junction and sino-tubular junction. The height of the Valsalva sinuses, from the aorto-ventricular junction to the sino-tubular junction, also corresponds to the diameter of the sino-tubular junction as alluded to in Figure 1. This is important as this can be used to assess cusp geometry after AVr. As an operative unit, the aortic valve includes both the aorto-ventricular and sino-tubular junctions, which combine to form the functional annulus and the cusps. To have good valve function is dependent on these two functional components working and performing synergistically and efficiently. To have a dysfunction in one of the aforementioned components is frequently associated with dysfunction of the other component. Therefore,

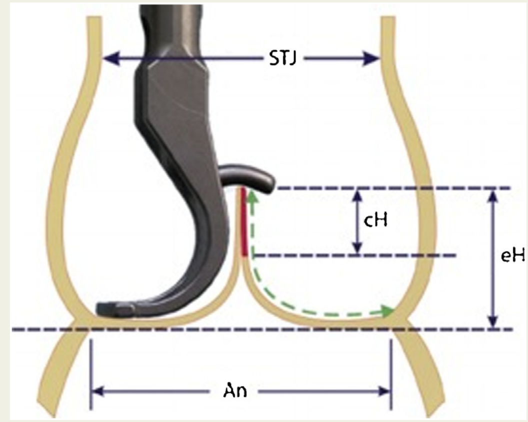

Figure 1 The principle of the effective height measurement with a calliper.
Abbreviations: STJ, sinotubular junction; cH, coaptation height (red line); eH, effective height; An, annulus; geometric height, green line (32).

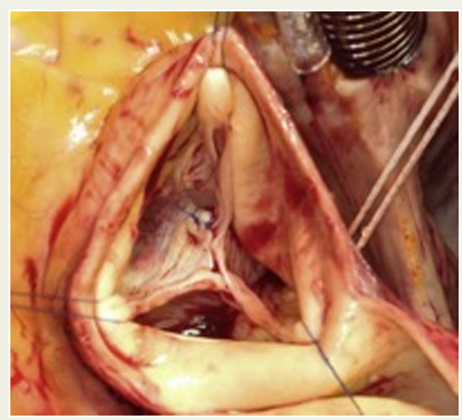

Figure 2 A figure to demonstrate the resulting status of the leaflets after plication suturing [32].

one of the most fundamental principles of AVr is that cusps and functional annulus should be addressed at the time of repair [4,32]. Figure 4 is a representation of Ozaki method of aortic valve repair. While Figure 5 represents intraoperative imaging of improvement in the flow and valve function post repair.

Sino-Tubular Junction

When the sino-tubular junction is dilated due to dilatation of the aortic root, the dilatation phenotype plays an important role in the manner of surgical intervention [3,32]. If the aortic valve is symmetrically dilated from the sino-tubular junction, the distance of the centre from the aortic valve commissures causes regurgitation. Therefore, a reduction in the sino-tubular junction may be performed by means of a supra-coronary ascending aorta replacement with a tubular graft; the repair of the valve is complete as the diameter of the tubular graft then defines the diameter of the sino-tubular junction [32].

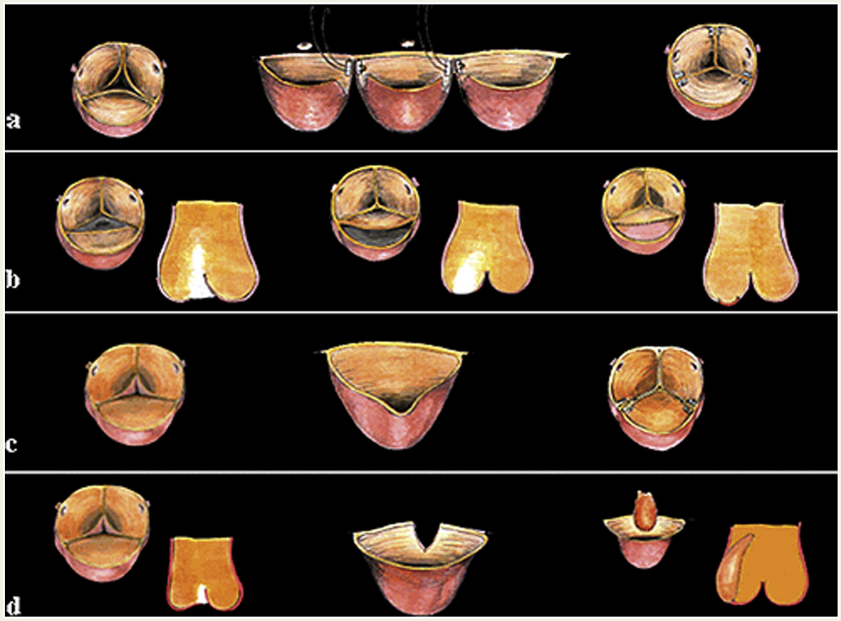

Figure 3 Schematic techniques of stages for aortic valve repair. A) commissural annuloplasty; B) enlargement of the cuspid; C) elevation of a cuspid by plication and D) for Valsalva sinus remodelling [63].

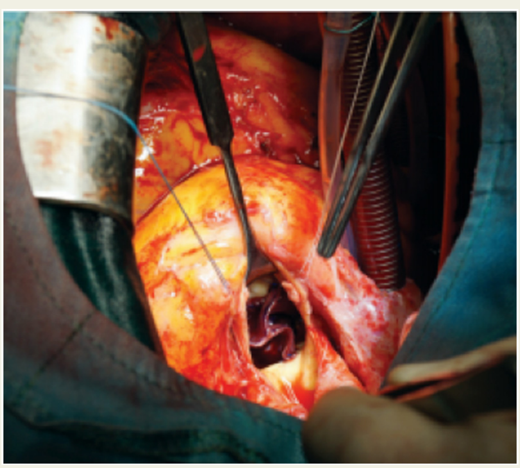

Figure 4 The Ozaki method or aortic valve reconstruction using pericardial tissue as bioprosthesis [69].

Aortic Sinuses

Also described as the sinuses of Valsalva, the aortic sinuses are one of the structures of the aortic root, the upper tier of which becomes the sino-tubular junction and tubular ascending aorta [33]. Dilation of one or more of these sinuses can lead to single leaflet dysfunction or, such as the widespread dilation that occurs in Marfan syndrome, annulo-aortic ectasia [33]. Aortic valve sparing techniques can be deployed when the valve leaflets are normal [34,35]. However, if the dilated aortic root is not addressed through either valve sparing aortic root replacement (VSRR) or conventional root replacement, then it will continue to dilate over time and become aneurysmal which mandates further extensive surgical repair.

Aortic Annulus

With reference to surgical intervention, the aortic annulus is regarded as the circular lines passing through individual leaflets. Whilst there is no anatomical correlation, the virtual landmarks define this basal ring [32]. The importance of a dilated aortic annulus in aortic regurgitation is sometimes overlooked, with some evidence suggesting that a dilated aortic annulus is an important risk factor to failed aortic valve repair [36]. One of the most popular techniques to reduce the aortic annulus used to be mattress sutures applied to the subcommissural triangles, which attempted to reduce the perimeter of the annulus; however, a circular stabilisation is not achieved which then leads to long term re-dilatation, which has led to the abandonment of the technique [37]. As a result of the shortcomings of this technique there have been others developed to achieve long-term stabilisation of the complete annulus.

The details of these different techniques are excessive to describe and are beyond the scope of this review. However, in principle they are classified as intra-aortic and extra-aortic annuloplasties [32]. The extra-aortic technique stabilises the annulus by means of an externally fixed ring such as the Coroneo ring [38]. Following this, the most popular intra-aortic technique is by use of suture annuloplasty which stabilises the sino-tubular junction with various rings [39,40].

Aortic Valve Leaflets

Aortic valve competence depends on the function of the aortic valve leaflets. The aim of surgical intervention of the aortic leaflets is to restore their normal function by achieving the normal formation. Early failure of AVr is influenced by the different degrees of coaptation of the leaflets [41]. Other factors which may influence AVr failure are the coaptation

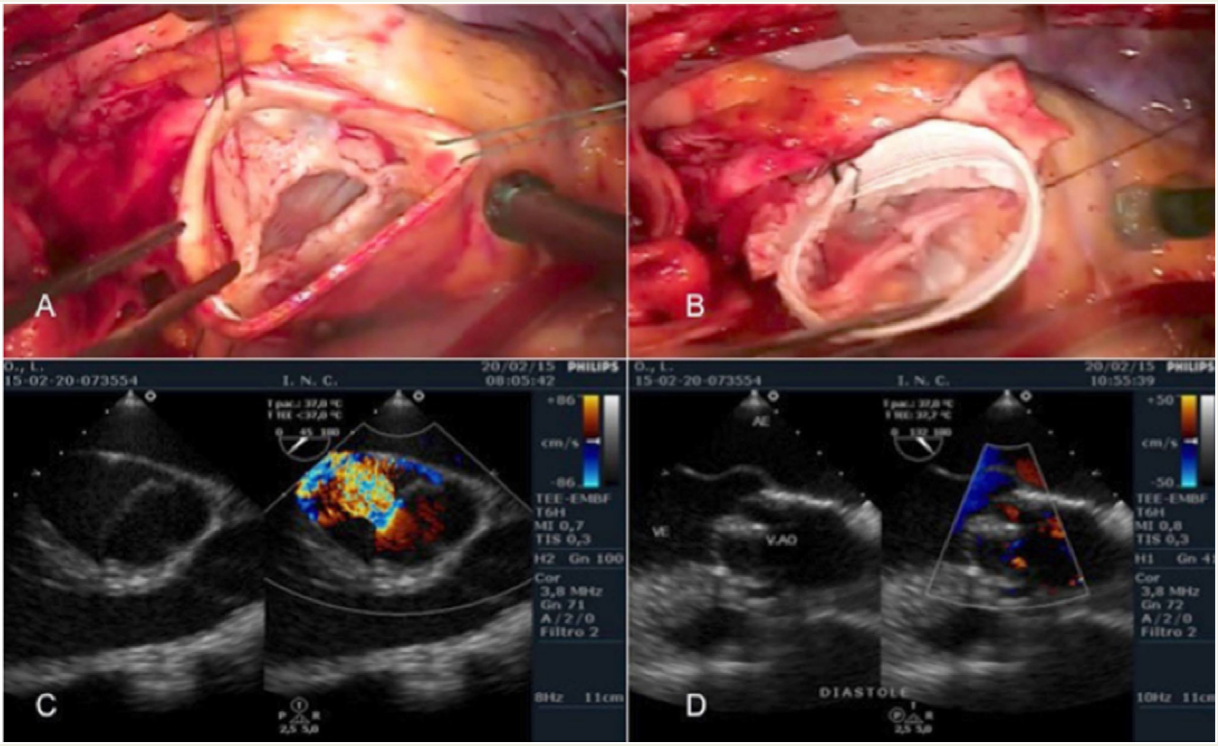

Figure 5 Repair of prolapsed and thickened bicuspid aortic valve using David technique of reimplantation. Intraoperative echocardiogram showing insufficiency before and improvement after repair.

height, effective height and geometric height as demonstrated in Figure 1. If the effective height is not sufficient, it may be enlarged by way of central plication by way of shortening the free margin in its central part (nodus arantii) [32]. After the leaflet is shortened, tension applies and the effective height is increased. This is a very efficient and frequently applied technique for AVr as shown in Figure 2. To achieve good long-term results and function in AVr, as well as effective height, the coaptation height is important. Coaptation height is the mutual contact between leaflets during diastole, this should be at least 4 mm (32).

Perioperative Outcomes

Evidence has shown that, in recent years, AVr is becoming more popular and the surgical intervention of choice; a recent analysis has shown AVr used in 6% of high risk cases, while in 25% of low risk cases [42]. The increase in frequency of AVr also needs to be evaluated with regards to the evidence for the technique. When considering if AVr is a viable alternative to AVR, it's important to be able to objectively measure this. As well as failure of the procedure, perioperative outcomes and long-term outcomes are important to consider and to compare. For AVr, results are not freely or widely available, therefore there is some debate on the durability of the repair and the prosthesis [43]. Also, to take into consideration are the risks that come with management of the patient following the surgical intervention. There are common results to be discussed which are applicable to any surgery such as operative mortality, results specific to cardiac surgery such as cardiopulmonary bypass time, as well as results which are more specific to valve surgery such as degree of valve pathology.

One group of patients which may pose a challenge when considering surgical intervention for the aortic valve is that of elderly patients. In a recent study of 815 patients (mean age 78 ± 3 years), intraoperative, 30 days and in hospital mortality was reported at 0%, 2% and 3% respectively [44]. Cardiopulmonary bypass and aortic cross clamp times on average were 156 ± 44 minutes and 100 ± 30 minutes respectively.

In a meta-analysis by Fok and colleagues, a total of 15 studies were used included in the summative outcome [45]. Seven studies focussed on bicuspid aortic valve (BAV) repair, five studies with cusp prolapse and then three studies which showed aortic valve repair in aortic root dilatation or aneurysm. In terms of patient characteristics, the study included nearly 5,000 patients who underwent aortic valve repair, with a mean age of nearly 51 years and just under 80% of patients of male gender. In-hospital mortality rate was reported to be 1.46%. Other evidence has also shown that early mortality in cases of AVr is around the 1% [42]. Whilst the study by Fok et al. reported outcomes based on the study pathology as described above, the outcomes showed AVr to be a well evidenced and well supported and favourable method of surgical intervention for aortic valves. In an earlier systematic review by Saczkowski et al. from 2013 varying degrees of early mortality rates between 0% and

3.6% were reported [46]. Whilst many factors will contribute to the different early mortality rates, this is a crude indication of the rates to be expected in aortic valve repair.

Other considerations for outcomes to be taken into account are those of neurological deficits, re-sternotomy and failure of the aortic valve repair. In the study conducted by Saczkowski and colleagues, it showed that a total of 11 studies reported a median perioperative neurological event rate of 1% (with a range of 0–7%) and a median re-sternotomy rate for bleeding of 3% (range 0–16%) [23]. While there was a median rate of 2% (range 0–16%) of requirement for reoperation in AVr [46].

Aortic valve repair is an attractive option for younger patients as it negates the need for life long thromboembolism compared to mechanical valve replacement. It offers favourable perioperative outcomes. However, due to the lack of comprehensive evidence in all patient groups, selection of AVr in specific patient groups is required. The increasing popularity of AVr as a treatment option and the increasing evidence to justify this option is testament to the potential of AVr.

Late Outcomes

Mortality

Long-term survival after valve sparing procedures has been compared favourably to those in valve replacement groups [35,47–50]. For aortic valve repair, survival at 5 years for a cohort of 640 patients (aged 56 ± 17 years) was 92%, and 80% at 10 years [51]. Freedom from valve-related mortality in a similar group (aged 53 ± 16 years) was quoted at 96.5% at 5 years and 80.5% at 10 years [52]. For those with bicuspid or unicuspid aortic valves of mean age 42 ± 14 years, there was a survival rate of 100% for the first 5 years postoperatively [53]. In a cohort of elderly patients at a greater operative risk, a study showed no difference between postoperative aortic valve repair survival at 5 to 8 years and that of the general population [44].

Late deaths are often associated with cardiac causes; in one study, 18 late deaths were caused by heart failure, sudden death, cancer, stroke or arrhythmia [54]. Risks for mortality were increasing New York Heart Association (NYHA) class prior to surgery, concomitant coronary artery bypass grafting and root replacement [51,55].

Reoperation

Although aortic valve repair is considered riskier than other techniques and may precipitate a need for further operations if the first is unsuccessful, systematic analysis of the quality of the tissue and method of repair allows for a successful repair [4]. Reoperation rates were approximately 92% after 5 years in one study, with no significant difference seen between preoperative AI [51].

Endocarditis, cusp retraction, aortic root dilatation, dehiscence of sutures, cusp prolapse, recurrent regurgitation and root dissection were reasons for reoperation [51]. Factors predisposing to failure are a higher NYHA classification prior to surgery, residual aortic insufficiency grade 2 at discharge, LV end-diastolic and end-systolic diameters [4]. Surgical techniques for valve prolapse such as use of a running Gore-Tex suture were seen with a better outcome, as was using more than one repair technique [4].

Marfan Patients

Connective tissue disorders such as Marfan syndrome have a higher risk of leaflet prolapse, causing AI [4]. Valve replacement has long been assumed to be the best procedure for Marfan syndrome, and yet the results for valve sparing and repair procedures remain promising. It is thought that the valves of connective tissue disease patients are generally well-preserved, making them ideal to correct the valve through repair [34]. In a study comparing 98 valve-sparing procedures against 67 Bentall for patients with Marfan syndrome, there was a 96.3% survival in the valve sparing group compared to the 90.5% in the Bentall group [35]. The operations for Bentall had older patients (mean age range 31–50 compared to 29–41, $p = 0.03$), with more aortic dissection and insufficiency, and more emergency operations, than the valve sparing group [35].

Aortic valve repair techniques in one study were examined in 146 patients aged 50 ± 15 years, resulting in a survival of 96% at 8 years [4]. In another, with an average follow-up of 6.1 years, across 518 patients who had tailored aortic valve repair, of 42 Marfan patients (43 ± 11 years), only one patient died due to alcohol-related toxicity [34]. There were no valve-related events, and reoperations were required in two patients who developed aortic dissection, but valves remained functional [34].

Aortic Insufficiency

A main cause of reoperation and difficulty in valve sparing and aortic repair procedures is AI. A number of patients in each study appeared to develop AI postoperatively, with most patients having some degree of mild insufficiency on echocardiogram; 20.6% in one study had minimal insuffiency and 7.1% Grade I AI [56,57]. Of these, a small number developed between moderate and severe AI; as many as 14.5% had at least moderate AI [47,54]. Severe AI often was an indication for reoperation [56]. In one study, 5.2% required reoperation for severe AI up to 5 years after the first operation [54]. For patients with bicuspid or unicuspid valves, rates were approximately 14% for reoperation due to recurrent symptomatic AI around 1 $^1/_2$ to 2 years after the initial surgery [53].

Causes of AI in valve repair that were severe and necessitating further surgical interventions were found to be re-prolapse of the cusp and suture disruption [54]. Moderate AI was caused by increasing NYHA status, aortic stenosis and endocarditis [54]. At the follow-up of valve-sparing procedures, NYHA status was recorded. After 20 years, 82% of patients in the study had a NYHA Class I, 13% Class II, and 5% Class III [47]. In another, at 15 years, 173 patients (85%) had NYHA Class I, 22 NYHA and 8 (4%) in Class III [10].

There are some differences between technique of operation and rate of insufficiency between the repairs. Studies suggest that reimplantation reduces aortic insufficiency in comparison to remodelling [47]. At echocardiogram follow-up, the amount of AR >1+ was significantly more in the remodelling group ($p = 0.05$) [35]. Similarly, the freedom from reoperation was lower in the reimplantation group [35].

Haemorrhage and Thromboembolic Risk

An advantage of valve-sparing procedures is the reduced bleeding and thromboembolism risk. Mechanical valves require lifelong anticoagulation to prevent emboli, which showed in one study with 15 haemorrhagic or thromboembolic events compared to the repair group, with only four (log rank $p < 0.001$) [35]. The Bentall group suffered intracranial haemorrhages, gastrointestinal bleeds, cerebrovascular accidents and thrombosis [35]. No haemorrhages occurred in the valve sparing group, with four cerebrovascular accidents occurring [35]. Similarly, aortic repair procedures have minimal haemorrhage and thromboembolism risk; 0.2% of patients were affected by a thromboembolic event at 5-year follow-up, and those requiring anticoagulation were for other medical conditions [51].

Is Valve Repair Replacing Valve Replacement?

In the 1950s, replacing the aortic valve was a new phenomenon. Every patient that needed aortic valve surgery was to undergo AVR. However, as the technique became established, more patients underwent elective valve replacement, more aortic valves were healthier when they were replaced, and surgeons began to explore the options of sparing the valve or repairing the damage to retain the valve. Over time, repairing the aortic valve has become more popular.

When considering replacement versus repair, this study has identified several key areas of comparison. In particular, the areas where valve repair has become widespread are among certain patient cohorts. Those at risk of thromboembolism or anticoagulation are less likely to be chosen for valve replacement due to the risk of lifelong side effects [8,9]. The risk of thromboembolic complications in AVr is lower, if not negligible, when compared to that of AVR [23]. Children are anticipated to grow and therefore are not ideal candidates for a fixed valve conduit, the size of which would not be consistent as they aged [9,27]. For further groups, an open discussion of repair versus replacement is essential.

For these groups, it is important, as noted earlier, to focus on the heart of the dysfunction when considering valve repair. Historically only normal functioning valves could be spared, but intra-aortic and extra-aortic annuloplasty corrects the dysfunction to restore normal flow, and not necessarily normal anatomy [7,32]. In an article on valve-sparing procedures, a question of variable outcomes between surgeons and techniques affecting long-term durability was raised [58]. Despite these reservations, both short-, mid- and long-term outcomes have showed positive results [34,36,53–55]. Mortality rates are similar, and in many cases no significant difference is found between the standard Bentall procedure [35].

Other long-term outcomes, such as rates of freedom from reoperation, compare favourably against bioprosthetic valve replacement [36,44,51,55]. It is also worth noting that when it comes to aortic valve sparing operations, reduced cardiac mortality and valve related complications can be seen when compared to composite valve graft procedures; AVr also shows better haemodynamic performance [4].

Despite these profoundly positive results, replacement is still extremely popular for a variety of reasons. It is a very successful and safe technique, developed over many decades of work [5,43,59–61]. The procedure can aid in left ventricular mass regression when hypertrophied, and the outcomes have been compared among more difficult cohorts such as small aortic root [59,62,63]. Conversely, AVr is still only the surgical intervention of choice in selected patients. These selected patients are operated upon in specific specialised centres, even then only by a few surgeons. Hence a large mainstay of procedures will inevitably be replacement, unless repair becomes a more standard operation.

The lack of randomised trials and non-randomised studies make it challenging to outline the role of AVr in the surgical management of aortic valve disease. Whilst comparison between valve-sparing procedures and replacement show equal outcomes, there are few comparing repair with replacement [35]. There is much more data when it comes to aortic valve replacement, this therefore makes it difficult to compare the two different techniques when it comes to evidence and indication. Further difficulty in comparing data arises between newer and older repair techniques, and the ongoing growth of the area; the evidence, techniques and the patient groups selected for AVr are constantly evolving. Therefore, studies may not necessarily reflect the current repair climate.

There are some very important challenges ahead for AVr. Firstly, in order to have AVr as a widely accepted surgical management option of aortic valve disease, there needs to be a range of techniques which address the variations in pathology when operating on the aortic valve. Replacement procedures have adapted over time to become widespread. The training of different surgeons is required to allow AVr to become more commonly performed. The increase in frequency of AVr may well have side effects in training surgeons to be proficient in this technique.

Another important challenge that is to be faced is of long-term outcome data. The long-term data then needs to be compared with mechanical and biological aortic valve replacement as well as any other methods of AVR. The emergence of transcather aortic valve implantation is now another viable treatment option in aortic valve pathology, this also needs to be compared to AVr for the best evidence in different patients. Comparison of the efficacy between repair and replacement would help to provide more concrete and up-to-date data.

Finally, it should be taken into account that repair or replacement should be considered per patient. Surgery for these groups requires individualised treatment based on their own needs and anatomy.

Conclusion

Over the past 50 years, the nature of aortic valve surgery has evolved 10-fold. Whilst aortic valve repair isn't new, in recent years the techniques and studies have reported encouraging results that rival the standard replacement procedures. Techniques have evolved, focussing on function rather than normal anatomy, and long-term mortality and reoperation rates have been shown to have no difference. If a long-term study between the two could be undertaken, further information regarding the efficacy of aortic valve repair could be given. Even if the two can be compared, there should still be individualised options that consider each candidate's anatomy and physiology based on personalised care.

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