Aortic Valve Reconstruction: Ninety Years of Progress

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**Origins of Aortic Valve Reconstruction “From Tuffier to Ross”**

The first documented surgery for acquired heart disease was in 1896. A stab wound of the heart was successfully repaired by Rehn [1,2]. On July 13, 1912 Tuffier preformed the first aortic commissurotomy in a 26 year old patient with progressive aortic stenosis [3]. Tuffier had reported six experimental aortic and pulmonary valvulotomies prior to this. His first human commissurotomy was done without opening the ascending aorta. He dilated the aortic valve digitally by indenting the wall of the ascending aorta. The patient went home twelve days after surgery and was still alive 12 years later [4].

In 1923, Cutler and Levine attempted to perform mitral valvulotomy for mitral stenosis [5]. They believed that resection of part of the stenotic valve was a necessary part of the procedure. Although the first patient survived, the next several died from mitral insufficiency. The procedure was abandoned for some years in the U.S. In England, in 1925, Henry Souttar performed a digital commissurotomy on one patient and although the patient survived, no further patients were referred to him for this unusual surgical intervention. The field of cardiac surgery was quiescent for over 20 years [6].

Russell Brock on March 27, 1946, passed a cardioscope through the innominate artery and visualized the calcified aortic valve [7]. In this initial case he did not attempt a valvulotomy. He later abandoned the retrograde approach to the aortic valve due to poor outcomes.

Charles Bailey and Dwight Harken independently worked at reviving the concept of digital commissurotomy for mitral stenosis. Charles Bailey performed the first successful closed mitral valvulotomy June 10, 1948 and this was followed six days later by Harken’s successful commissurotomy [8,9]. This ushered in an era of mitral valve surgery that spread throughout the world. However, due to the limited extent of relief of mitral stenosis achieved by digital commissurotomy, in 1959 a mitral valve dilator was developed in England by Tubbs, Logan and Turner [7]. This permitted a more extensive commissurotomy, but was sometimes attended by postoperative mitral insufficiency.

On June 22, 1950, Charles Bailey performed a transventricular dilatation of aortic stenosis and over the next two years repeated this procedure eleven times [7]. Although he had a 33% mortality rate, some of the survivors were greatly improved. Because of the limitation in the relief of aortic stenosis using this technique, he turned to an expandable triradiate instrument which produced better and more predictable results. In 1954, William Muller described his experiences with the treatment of aortic valve stenosis in 16 patients who had aortic valve stenosis only, and an additional 9 patients who had either aortic and mitral valve disease or aortic stenosis and coarctation of the aorta [10]. There were four deaths in the aortic valve only group, and two deaths in the nine patients with dual deformities. By 1952, Brock was dilating the aortic valve with an instrument passed through the left ventricle [7]. Gibbons first use of the heart lung machine in 1953 paved the way for an explosion of cardiac surgical procedures [4]. In November of 1955, Henry Swann performed an open aortic commissurotomy through an aortic incision using hypothermia [7]. Five years later he reported in the British Medical Journal the outcomes of his series of patients undergoing aortic commissurotomy using hypothermia. Early in the series, in cases of severe aortic stenosis, there was a mortality between 25 and 50%. However, the overall mortality was about 5% with 75% of the survivors having a good result. In 1958, Dwight Harken documented his outcomes in 100 patients who had closed transaortic digital dilatation of the calcified aortic valves [11]. He used an Ivalon sponge tunnel or graft attached to the ascending aorta. Through this his finger was placed into the ascending aorta to do the valvular dilatation. There were 16 deaths in these 100 patients. There were 7 deaths in the first 20 patients, and only 5 deaths in the last 60 patients [11]. On January 31, 1956, Walton Lillehei used the heart lung machine with a bubble oxygenator. Lillehei opened the commissures to the annulus with stout dissecting scissors, and he trimmed off some of the calcium deposits helping to restore mobility to the leaflets [12]. The patient made a uneventful recovery.

**Aortic Valve Regurgitation**

Charles Hufnagel led the early attempts at surgically treating aortic valve regurgitation. In 1952 he implanted a caged ball prosthesis in the descending aorta where it prevented approximately 70% of the regurgitation in the aortic valve (Figure 1) [13]. Hufnagel’s visionary work was followed by a variety of techniques and prostheses designed to replace the aortic valve. In October 1955, Gordon Murray replaced the aortic valve of a 22 year old man with a homograft valve taken at necropsy from a 33 year old man, and preserved in physiological saline solution at 4o centigrade for 36 hours [7]. It was inserted into the patient’s aorta at the level of his sixth thoracic vertebra. Eighteen months later the man was doing heavy manual labor.

A new reconstructive technique tried in this area was bicuspoidization (the conversion of a trileaflet aortic valve into a bileaflet aortic valve). On May 23, 1956, Walton Lillehei operated on a woman of 52, who had a mixed lesion of aortic stenosis and regurgitation [12]. He corrected this valve by...
inserting two mattress sutures to turn the valve from an incompetent tricuspid one to a bicuspid one with better apposition of the leaflets. This patient was greatly improved, and Lillehei used this technique in January 1958, to treat the pure aortic valve insufficiency in a 45 year old man [4]. This bicuspidization became quite popular in this era.

Bahnsen 1960, Harken 1960, McGoon 1961, and Lillehei 1961, all reported successful partial prosthetic replacements of the aortic valve (Figure 2) [7]. However, results of partial valvular replacement were often found to be less than satisfactory. In the latter part of 1958, Lillehei and Muller separately and independently replaced the entire aortic valve with a prosthesis [14]. Muller in his first complete valve replacement used compressed Ivalon sponge to replace the leaflets, but his valve prosthesis (the Muller valve) was used in 1959 (Figure 3) [15]. The development of a ball-valve prosthesis by Albert Starr in 1960, was a significant advance in aortic valve surgery (Figure 4) [16]. However, all of the early mechanical valve substitutes have been abandoned or undergone multiple modifications because of structural failure or postoperative embolic complications. Emerging from this era, several mechanical prosthesis have provided good quality long lasting results for patients with aortic valve disease. (One of the authors gets his hair cut regularly from a patient in whom he placed a model 1260A Starr-Edwards prosthesis on 6/13/1978.) On July 24, 1962, Donald Ross implanted a freeze dried homograft aortic valve after an aortic valvulotomy went awry, and the patient had an uncomplicated recovery [17]. In 1967, Ross reported a small series of autograft replacement of the aortic valve [18].

Aortic Valvuloplasty in Young Patients
With improvements in cardiopulmonary bypass and myocardial protection, surgeons have been able to make more precise attempts at reconstructive surgery of the aortic valve. The sequelae of Rheumatic fever throughout the world has resulted in a large number of young people with chronic valvular disease involving principally the mitral and aortic valves. Obviously, if these valves could be repaired and have good durable function without life long anticoagulation (which is an absolute requirement after mechanical valve replacement) then it would be a much improved quality of life and length of life for all these patients. Thus, in the late 1970’s and 1980’s there was renewed interest in reconstructive procedures of both the mitral and aortic valve, throughout the world.

Techniques of Aortic Valvuloplasty
The routine use of cardiopulmonary bypass allowed precise delineation of the extent of the pathological process and optimized the opportunity for multiple reparative procedures to improve the stenotic or regurgitant valves. Although many authors in the late 70’s and 80’s described their early experience with aortic valvuloplasty, Carlos Duran in 1991 outlined his multifaceted corrective techniques as well as the longer term postoperative outcome [19]. His patient population was young (average mean age of 23 years) and 84% of his patients had a history of Rheumatic valve disease. One hundred seven patients had aortic valve repair or reconstruction. Forty two of these had aortic valve surgery only, forty three had concomitant mitral valve repair and twenty two had aortic, mitral, and tricuspid valve surgery. The operative repair or reconstruction consisted of commissurotomy, subcommissural annuloplasty, free edge unrolling, cusp resuspension, and supra-aortic crest enhancement. In patients where there was considerable shrinkage of the aortic leaflets, (gross retraction of more than of the leaflet area) cusp extension was performed [19]. In this situation the thickened part of the cusp was resected leaving a rim of 5 mm of leaflet tissue. A rectangular strip of glutaraldehyde-treated pericardium was then cut in a tricuspid fashion and sutured to the leaflet remnants. The new commissures was anchored to the aortic wall and the sutures were tied over the pledgets on the outside of the aortic wall. The first 25 of these leaflet extension patients had commercially available bovine pericardium used; the last 13 had autologous pericardium as the cusp extension [19].

Duran’s series showed that superb results could be achieved with aggressive valve conservation techniques in young patients with Rheumatic valve disease. This series revealed very good early and intermediate term results with freedom from aortic valve reoperation at 30 months for the cusp extension cohort of 94%; in the repair cohort with freedom from aortic reoperation at 30 months was 77% [19]. A review of longer-term results obtained in a group of 50 patients, who underwent operation with these techniques between 1974 and 1986, showed a 13 year actuarial survival of 86%, and only four reoperations due to severe aortic valve dysfunction [20].

Other authors described the use of bovine pericardium or autologous pericardium in both aortic and mitral valve repair operations. Al Fagih documented how he individualized the bovine pericardial patch for each cusp extension rather than using one rectangular segment for all three cusps [21]; Chauvaud et al. detailed the use of glutaraldehyde-preserved autologous pericardium to extend the leaflets (both anterior and posterior leaflets)-in mitral valve reconstructive procedures [22]. Chauvaud’s patients had a mean age of 19 years, 69% of them had Rheumatic valve disease and the mean follow up was 3.1 years. Only 12% of his patients came to reoperation during that time.

In 1998, Kalangos described his experience in Geneva using fresh autologous pericardium to repair the aortic valves in 41 patients who had severe rheumatic aortic insufficiency [23]. The mean age was 11.5 years and twenty-four of these 41 children underwent concomitant mitral valve repair for associated rheumatic mitral valve disease. Follow up ranged from 3 months to 5 years (a median of 3 years) with no operative or early follow up deaths. One patient died nine months after operation of septicemia and multiple organ failure. Actuarial survival was 97% at one year and no patient required reoperation for aortic insufficiency during the follow up period [23]. Kalangos illustrates quite beautifully his technique of cusp thinning and subsequent fresh autologous pericardial cusp extension in his article, and his excellent results in this group of very young patients is quite encouraging.

In 1983, Carpentier reported that it was feasible to repair congenital malformations of the aortic valve in about 80% of patients [24]. However, in Rheumatic valve disease, he felt that successful valve repair was feasible in only about 5% of
Figure 1. The ball-cage valve of Hufnagel implanted in the descending thoracic aorta using the multi-point fixation rings.

Figure 2. The Bahnson leaflet used to replace a segment of the native aortic valve.

Figure 3. The Muller valve constructed from Teflon, circa 1959.

Figure 4. The Starr-Edwards ball-caged prosthesis developed in 1960.

Figure 5. Acute type A aortic dissection with disruption of the ascending aorta and aortic root.

Figure 6. Careful re-suspension of the commissures allows the valve to be saved.
patients, and limited to moderate aortic incompetence with preserved pliability of leaflet tissues. He emphasized felt that the calcified aortic valve was a contraindication to reconstruction [24]. Overall in the young patient population, the use of reparative techniques and cusp extension in Rheumatic valve disease patients provides a very effective quality of life and avoidance of mechanical valve replacement in these patients with aortic stenosis.

Aortic Valve Repair in the Elderly

Traditionally, mechanical debridement of calcific aortic stenosis in elderly patients was followed by encouraging early results. However, there was little long term follow up to document the efficacy of such therapy. In the 70’s and 80’s, many authors were interested in the conservative treatment of the calcified stenotic aortic valve. In 1972 ultrasonic debridement was introduced by Brown and Davis [25,26]. The concept lay dormant for 15 years. There was a resurgence of interest for debridement of calcific aortic stenosis and a number of authors demonstrated that aortic stenosis could be effectively relieved without causing intraoperative aortic insufficiency [27,28]. In 1991, Leithe and associates described their experience with the Cavitron ultra-sonic surgical aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultra-sonic surgical aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique. In 1991, Leithe and associates described their experience with the Cavitron ultrasound aspirator in 10 patients [29]. At an average follow up of eight months, six had an increase in the degree of aortic insufficiency, and the authors felt that this was likely to limit the application of this technique.
Acute aortic dissection has resulted in different types of surgical reconstruction of the proximal aorta and aortic valve over the last three decades. Such operative procedures as repair or replacement of the ascending aorta, aortic valve re-suspension and replacement of the proximal ascending aorta (Figure 5-7), composite graft replacement with a prosthetic aortic valve and a prosthetic ascending aortic graft have been commonly used. Gelantine-Resorcin-Formaldehyde glue (GRF) has been used over the last 15 years with great effect in Europe [32]. Biological glues are now being used with increasing frequency in the United States. In the 1970’s and early 1980’s, in acute aortic dissection with severe regurgitation of the aortic valve, attention was focused on a composite replacement of the ascending aorta [33-35]. Over the last 15 years, more interest has revolved around valve sparing operations on the aortic root and the ascending aorta. A number of authors including Yacoub and David, have emphasized the feasibility and desirability of the valve sparing procedures [36-46].

David reported 120 patients operated on between May of 1988 and June of 2000, who underwent valve-sparing proximal aortic surgery [43]. Forty-eight of these patients had Marfan’s Syndrome and 22 had either acute or chronic Type A aortic dissection. The ten year survival of these patients undergoing a variety of complex proximal aortic reconstructions was 88%. The ten year freedom for aortic root reoperation was 99%. David emphasized precise and critical analysis of the anatomical dimensions of the aortic root, the aortic valve, the sino-tubular diameter, and the size of the aortic sinuses [40]. The diameter of the ascending aorta was also important. He feels that in reconstructing the aortic root, every attempt should be made to re-attain certain fundamental dimensions and ratios of the aortic root: (The length of the base of the aortic leaflet is approximately 1.5 times longer than the length of the free margin; The diameter of the aortic root is approximately 15-20% larger than the diameter at the sino-tubular junction; Remodeling of the aortic root can be achieved by correcting the dilated sino-tubular junction - this can be accomplished by replacing the ascending aorta with a tubular Dacron graft with a diameter that is 5-10% smaller than the average length of the free margins of the valve leaflets.) In an easy, “cookbook” style, he describes clearly the techniques used for single leaflet prolapse causing aortic regurgitation, for regurgitation by a bicuspid aortic valve, for regurgitation caused by dilatation of the sino-tubular junction which can be corrected by remodeling of the aortic root and replacement of the ascending aorta with a smaller graft [43]. Such technical issues as tailoring of the proximal end of the tube graft to replace the aortic sinuses are clearly emphasized. In the dilated aortic root, he described remodeling with a strip of Dacron felt and interrupted sutures to make the root smaller as part of a valve-sparing operation. David and Yacoub both emphasized aggressive reconstruction of the root using different valve sparing techniques in acute Type A dissection [42,46]. This involves not only re-suspension of the valve, but excision of all proximal ascending aorta and aortic sinus tissue. The use of these techniques in Marfan’s patients has been justified by the excellent long term survival and low incidence of reoperation by these authors [39].

In April of 2000, Cochran demonstrated with geometric models how he felt David’s valve-sparing procedure should be modified [47]. This resulted in the “Cochran modification of the David procedure”, with the resultant “pseudo sinus” change in the cylindrical graft. From a theoretical perspective, this modification has a lot to recommend it, and the creation of sinus areas in the prosthetic graft perhaps will result in less stress falling on the valve leaflets. David feels that aortic valve sparing repair is feasible if a) The leaflets are normal or have minimal disease, b) If the leaflet prolapse alone is causing aortic valve insufficiency, c) Dilatation of the sino-tubular junction is causing aortic valve insufficiency, d) Dilatation of the aortic annulus is the cause of the valvular insufficiency, or e) In a bicuspid valve with minimal dilatation of the ascending aorta, the aortic insufficiency is caused by prolapse of one of the two leaflets [40]. This is repairable unless there is severe leaflet disease. David feels that repair should not be undertaken if there is severe degenerative disease of the aortic valve with thinned or over-stretched leaflets, or if there is severe rheumatic disease with fibrotic, fused, or shrunken leaflets. In these conditions he feels that valve replacement is preferable. Duran, feels that in the rheumatic scenario aggressive valve leaflet reconstruction or cusp extension provides excellent long term results.

**Late Results**

Long term survival for patients with Type A aortic dissection in some series has been somewhat disappointing. Kazui and associates have reported on 130 patients who underwent surgical intervention for acute Type A dissection [48]. Eightytwo of them had total arch reconstruction, 29 had a semi-arch and 19 had resection of the ascending aorta, only. They had a 19.2% in hospital mortality, and the actuarial survival rate at ten years was 70.9% and freedom from reoperation was 73.5% at ten years. They found that aortic valve re-suspension, which was performed in 42 patients was an independent predictor of proximal aortic reoperation, whereas non-resection of intimal tear and younger age were independent predictors for distal reoperation [48]. Kirsch and associates reported a twenty year experience from 1980 to the year 2000, with a total of 160 consecutive patients who underwent surgery for acute Type A dissection [49]. Proximal repair consisted of ascending aortic replacement with valve re-suspension in 130 (81.3%) patients, composite graft replacement in 19, and separate aortic valve and ascending aorta replacement in 7 cases. Distal repair required arch replacement in 23 cases. There was an average follow up of 4.5 years and survival at 10 years was 52.2%, and at 15 years 42.5%. 30 patients required 37 reoperations at a mean interval of 5.7 years after the initial operation. Freedom from reoperation was 60.8% at ten years and 39.3% at fifteen years. The authors felt that patients with acute Type A aortic dissection who have severe aortic valve insufficiency are at increased risk for proximal reoperation, and perhaps a more aggressive proximal repair at the initial operation would be beneficial. They also felt that the distal extent of the aortic resection at the initial operation did not significantly influence the risk of distal reoperation [49].

Perhaps David’s hypotheses that the diameter of the sino-tubular junction needs to be restored, and the diameter of the ascending aorta immediately above that junction needs to be smaller than the diameter of the sino-tubular junction, both
play a role in the reoperation rate of proximal aortic surgery patients who have valve suspension and ascending aortic grafting. This would certainly be an easy thing to address and study.

**Pulmonary Artery Autograft and Homograft Replacement of the Aortic Valve**

In 1967, Donald Ross used a patient’s own pulmonary valve to replace the aortic valve, and used a homograft pulmonary valve to replace the transplanted pulmonary valve [7,18]. At the time, this was felt by many to be a cumbersome technique of aortic valve replacement. Some people felt it was turning single valve disease into double valve disease in the same patient. However, Ross’s visionary work gradually spread to different centers around the world and this has become a standard replacement technique in people of the younger age group with severe aortic valve disease.

In the United States, Ronald Elkins in 1999, described his experience with 328 patients who had a Ross operation at the University of Oklahoma [50]. The overall operative survival was 95.4%, with an actuarial survival of 89% at 8 years. Of significance was the fact that freedom from replacement of the pulmonary autograft was 94% at 8 years, freedom from reoperation on the pulmonary homograft was 90% at 8 years and freedom from autograft valve reoperation or dysfunction (3+ autograft insufficiency) was 83% at 9 years.

Magdi Yacoub and associates in 1997, compared the pulmonary autograft procedure to homograft replacement of the aortic valve in a prospective randomized trial [51]. Of the 70 patients randomized, 37 received an aortic homograft, while the pulmonary autograft cohort was 33 patients. The mean age was 39 years in the homograft group and 29 years in the pulmonary autograft group. Eleven patients (30%) in the homograft group and 8 (24%) in the autograft group had undergone previous aortic valve surgery. All patients were operated on by the same surgeon. In 86.5% of the homograft patients the homograft was implanted as a root, and in the pulmonary autograft patients, all the autografts were implanted as a root. Although there was a statistically significantly longer cardiopulmonary bypass time and cross clamp time in the autograft group, there were no early deaths in either group and no late deaths in either group at a mean follow up of 16 months. Yacoub felt that although the pulmonary autograft required longer operating time, this did not seem to be a factor in terms of morbidity and mortality observed in autograft patients, when compared to homograft patients.

The longest follow up of pulmonary autograft patients was the series of Donald Ross [52]. These 131 survivors of the pulmonary autograft operation between 1967 and 1984, have been followed up until 1994, and the long term results were reported in 1997. The operative procedure in 107 patients was an orthotopic sub-coronary implantation of the pulmonic valve, it was a free standing root in 20 patients, and in 113 of these patients homografts were used to replace the pulmonary valve. The 10 and 20 year patient survival was 85% and 61%; the 10 and 20 year freedom from autograft replacement was 88% and 75%; the 10 and 20 year freedom from replacement of the pulmonary homograft was 89% and 80%. Ross felt that autograft regurgitation was primarily technical and this was the commonest cause of autograft reoperation. There was a low rate of degeneration of the autograft valve that required reoperation (3 out of 30 patients who came to reoperation), and there was a low incidence of endocarditis or thromboembolism. Ross felt “the capacity of the autograft to maintain viability with minimal degeneration is not matched by any other biological valve replacement”.

**Homograft Replacement of the Aortic Valve**

On July 24, 1962 Donald Ross implanted a freeze-dried homograft aortic valve into a patient after an aortic valvulotomy did not work, and the patient made an uncomplicated recovery [17]. In 1965, Barratt-Boyes and associates reported the initial two year experience at the Green Lane Hospital in New Zealand with homograft replacement of the aortic valve [53]. Forty-two patients had aortic regurgitation only, 48 patients had aortic stenosis only, and 11 patients had multivalvular disease. There were six deaths in-hospital, and eight deaths on late follow up. These authors achieved excellent results in this early era of homograft replacement. Of 93 patients followed closely, only five had moderate aortic regurgitation and four had severe aortic regurgitation. A later report of longer term follow up on these 101 patients showed that reoperation was undertaken in 17 patients. The causes of reoperation were peripheral leaking of the suture line, cusp rupture, bacterial endocarditis and valve misplacement. Leaflet calcification causing valve stenosis resulted in reoperation in two patients and was significant in eight other valves. The authors felt that a cusp rupture problem and leaflet calcification were related to the valve preparation and for this reason chemical sterilization and freeze drying were replaced by sterilization and storage in antibiotic Hanks solution.

Mark O’Brien in 1966, reported successful homograft valve transplantation in a 32 year old patient [54]. In 2001, he and his coauthors reported a 29 year experience with homograft aortic valve replacement in 1,022 patients. These patients underwent surgery from 1969 to 1998 and had a median age of 49 years (the range was from 1-80 years). 635 patients received a sub-coronary valve replacement, 35 received an intraluminal cylinder, and 352 had a root replacement. There was a 99.3% complete follow up of this very large patient cohort. Concomitant cardiac procedures were performed in 25% of patients (usually coronary artery bypass grafting or mitral valve surgery). 9% of patients had acute active endocarditis. The 30 day/hospital mortality was 3% overall, falling to 1.13% for the 352 patients who had a homograft root replacement. Actuarial late survival at 25 years for the whole cohort was 19%. Preservation methods (4° centigrade or cryopreservation) and implantation techniques showed no difference in the overall actuarial 20 year incidence of late survival, endocarditis, thromboembolism, or structural degeneration requiring reoperation. Freedom from reoperation from all causes was 50% at 20 years and freedom from reoperation for structural deterioration was patient age dependent. For all cryopreserved valves at 15 years follow up, the freedom from reoperation was 47% in the 0-20 year old cohort, 85% for the 21-40 year old cohort, 81% at the 41-60 year old cohort, and 94% for the greater than 60 year cohort. Root replacement versus sub-coronary implantation reduced the technical causes for reoperation and re-replacement. This impressively large group of patients with almost complete follow up for the longest
period of time demonstrated the excellent advantage of the homograft aortic valve for the treatment of acute endocarditis, and for use in people older than 20 years of age. However, their experience with young patients (under the age of 20 years) revealed a 47% freedom from reoperation at 10 years and the authors felt that alternative valve devices were indicated in this cohort. Elkins’ broad experience with the Ross procedure in this age group makes this the valve substitution of choice in these young patients [55].

Over the last 20 years in the United States homograft replacement of the aortic valve has been used especially in younger patients, in patients with an infected aortic root, and in patients where avoidance of long term anticoagulation was important. The excellent long term survival and freedom from reoperation statistics of Brian Barret-Boyce and Mark O’Brien catapulted surgeons in the United States into following into their footsteps, and the footsteps of Donald Ross and Magdi Yacoub.

In 1999, Knott-Craig, Elkins, and Associates presented comparison of the late survival between autografts and homografts in patients with aortic valve disease [56]. They presented the outcomes in 238 hospital survivors between the ages of 17 and 82 undergoing operation between 1986 and 1999. All the procedures were done as root replacements, and patients requiring concomitant other valve replacement were excluded. The mean age of the 145 autograft patients was 35 years, and the mean age of the 93 homograft patients was 49 years. Of significance was the fact that previous aortic valve replacement had been done in 8% of the autograft patients and 34% of the homograft patients. Active endocarditis at the time of surgery was present in 7% of the autograft patients and 27% of the homograft patients [56].

The maximum follow up was 12.2 year for autografts and 12.8 years for homografts. The late survival at 10 years was 77% for autografts and 67% for homografts; freedom from autograft or homograft degeneration at 10 years was 97% and 79% respectively; freedom from valve related complications at 10 years was 73% and 64% respectively. Freedom from all reoperations at 10 years was 88% in the autograft cohort and 72% in the homograft cohort. These authors felt that autografts and homografts have comparable late survival, and the incidence of valve degeneration is low for both valve substitutes up to 8 years, at which point there may be a trend towards an advantage of autografts over homografts, suggesting that autograft replacement may be beneficial for younger patients [56].

Jaggers and associates, from Duke University, did an interesting comparison of the postoperative length of stay, morbidity, and the costs for patients undergoing the Ross procedure as compared to patients undergoing a mechanical aortic valve replacement between 1993 and 1996 [57]. There were twenty-two consecutive adult patients in the Ross cohort, and 27 patients in the mechanical valve replacement cohort. There were no hospital deaths in either group and there were two late deaths in the mechanical valve replacement group. The length of stay postoperatively for the Ross procedure was 5.9 days versus 8 days for the mechanical valve group. The mean hospital costs were not significantly different, being $23,140 for the mechanical valve group versus $23,226 for the Ross procedure group. The authors felt that this small series demonstrated that Ross procedure patients can have a short hospital stay, decreased morbidity, and equal hospital costs when compared to patients undergoing a standard mechanical aortic valve replacement [57].

**Heterograft Root Replacement**

Although many thousands of patients requiring aortic valve replacement have undergone implantation of a stented porcine bioprosthesis, in many centers in the United States, this prosthesis is most frequently used in patients over the age of 60 years. In younger patients, there has been a fairly predictable life span for the porcine bioprosthesis, and these patients with these implants can plan on having repeat valve operation later in life [58-60]. Certainly in elderly patients, the porcine bioprosthesis has been a splendid choice for implantation as the elderly patients do not outlive the duration of function of their bioprosthesis. During their postoperative life they do not have to worry about the risks of long term anticoagulation. This is an enormous benefit for these elderly patients.

In patients with a small aortic root, the implantation of a stented porcine heterograft can leave the patient with a relative degree of residual aortic stenosis, and delayed resolution of the preoperative left ventricular hypertrophy.

In the year 2000, Gelsomino from Udine, Italy, reported their group’s experience with the Cryolife-O’Brien stentless porcine aortic bioprosthesis [61]. This prosthesis is a composite design, manufactured from the non-coronary leaflets obtained from three porcine valves. The leaflets are excised from valves already fixed in glutaraldehyde under very low (near 0) pressure. The matched set of leaflets is sutured together along the free edges of the porcine aortic wall at the leaflet commissures. The 30 day mortality was 3.1% and the five year actuarial survival was 93.9%. The authors felt that there was a decreased incidence of patient-prosthesis mismatch, and an increased resolution of the LV massindex. They felt that this might be translated into improved long term survival [61].

In 1999, Kon reported his group’s experience with 112 patients operated on from September 1992 to April 1998 [62]. All patients received an aortic root replacement with the Medtronic Freestyle stentless porcine bioprosthesis. There were 4 deaths within 30 days for an operative mortality of 3.6% and no structural valve deterioration at 5 years. The 5 year patient survival was 82.8%, and the freedom from thrombo-embolic events was 90.5%. The authors illustrated beautifully the technique of root replacement and gave important information about intermediate term survival data [62].

In the year 2000, Riley, Kon, and Associates reported data comparing stentless aortic valve replacement with the Medtronic Freestyle prosthesis to replacement with the Toronto SPV prosthesis [63]. In a two year period from May 1997 to 1999, 58 patients underwent aortic valve replacement with a stentless porcine bioprosthesis. Forty-four of these were the Freestyle prosthesis using a total root technique, while 14 were the sub-coronary Toronto SPV bioprosthesis. Sixty-four % of both groups underwent concomitant cardiac procedures. While the ischemic times were comparable (117 minutes for the Freestyle and 124 minutes for the Toronto SPV patients) the mortality was the same in both groups. There were no operative deaths and no valve related re-operations. The effective orifice areas were the same in both cohorts. The transvalvular gradient was 8.03 mm of
Hg for the Freestyle cohort and 12.4 mm of Hg for the Toronto SPV cohort. While there was no aortic regurgitation seen on follow up in any patient in the Freestyle cohort, there was some regurgitation present in the Toronto SPV cohort - this was graded as none to trace in 79%, mild in 14%, and moderate in 7%. The authors concluded that while aortic valve replacement with either prosthesis required equal time for implantation and resulted in equal effective orifice areas with both prostheses, the Freestyle had a lower transvalvular gradient and less aortic insufficiency in this short term follow up period [63].

In 2001, Cohen and associates from the University of Toronto, reported interesting results when they compared the outcome of stentless bioprosthetic valves to stented valves [64]. This was a prospective randomized trial in which 53 patients received the stented Carpentier-Edwards pericardial valve, and 46 patients received the Toronto stentless porcine valve. Although the cardiopulmonary bypass times were longer in the SPV cohort (148.5 minutes versus 118.6 minutes) and the aortic cross clamp times were longer in the SPV patients (123.6 minutes versus 95.4 minutes), perioperative morbidity and mortality were similar in both groups. Surprisingly, neither replacement valve offered a superior internal diameter for any given annular diameter. Although the labeled mean valve size was significantly larger in the SPV group, the actual mean valve size based on internal valvular diameter was no different between groups. Again, the effective orifice areas in both groups increased with time, and the mean and peak transvalvular gradients in both groups decreased over time, but there were no differences noted between the groups at 12 months. Similarly, although significant regression of left ventricular mass was accomplished in both groups over time, there were no differences demonstrated between the groups. The authors concluded that although the stentless SPV valve patients had excellent outcomes, they did not demonstrate superior hemodynamics when compared to patients undergoing stented pericardial valve replacement at 12 months follow up [64].

In an era where there is limited availability of homograft aortic valve replacement at 12 months follow up [64]. The enlargement of the annulus was achieved by doing the Manouguian procedure and while the mortality in the patients who had a simple valve replacement was 3.5%, it rose to 7.1% in the patients who had the enlargement of the aortic annulus. Although it did not reach statistical significance, the difference in mortality was impressive [68].

With modern mechanical valves and bioprosthetic valves, attention is focused on a larger effective orifice area and a smaller prosthetic annulus. Thus, the use of these annulus enlargement techniques has become much more frequent. Most patients do quite well with a smaller valve carefully implanted and do not require enlargement of the aortic root. Because of the impressively low morbidity and mortality statistics reported for re-do aortic valve replacement procedures, many younger patients in the United States opt for a decade or two of anticoagulant-free survival after a bioprosthetic aortic valve replacement, and then plan to have their re-do valve replacement in the decades ahead [69-72]. This clearly obviates the morbidity associated with long-term coumadin therapy and improves the quality of life for the duration of function of the bioprosthetic valve.

Currently, many centers throughout the United States will use a Ross procedure for patients up to the age of 50 years who require aortic valve replacement. If there is availability of homografts, and in patients from 50-65 years of age, a homograft root replacement will be used. Certainly, for patients 65 years or older who require aortic valve replacement a porcine bioprosthesis has wide spread application. In patients with SBE and especially if they have an aortic root abscess, a homograft root replacement will be the valve of choice no matter what age patient is affected.

Alternatively, in patients who have no contraindications to life long anticoagulation with Coumadin, and in patients who fear the possibility of a reoperation, the use of a mechanical valve has wide spread acceptance. With increasing frequency, patients who have done considerable research using the Internet will want to discuss the valve replacement options with their cardiologists and surgeons, and be active participants in the decision as to what valve prosthesis they wish to have implanted.

**Hypertrophic Obstructive Cardiomyopathy**

Spirito et al, outlined clearly the medical treatment of patients with hypertrophic obstructive cardiomyopathy that resulted in subvalvular left ventricular outflow tract obstruction (L.V.O.T.)
The medical management of such patients depends in part on the clinical presentation e.g. heart failure, atrial fibrillation, or the absence of symptomatology. For failure of medical therapy dual chambered pacemakers have been beneficial in some patients. To prevent sudden death in these patients, Amiodarone has been used as well as implantable defibrillators. However, patients with high resting gradients in the L.V.O.T., and patients who have failed medical treatment traditionally have undergone myotomy and myectomy as described by Morrow in 1975 [74]. Merrill and associates described their follow up in 22 patients who underwent septal myectomy with a follow up ranging up to 17 years (a mean of 6.6 years) [75]. There was zero hospital mortality, a zero percent incidence of ventricular septal defect, zero percent incidence of permanent pacemakers in this operative cohort, and no residual obstruction in the LVOT. There were two late deaths at 6 and 9 years postoperatively. Echocardiography at late follow up showed decreased thickness of the septum and the posterior left ventricular free wall, and an increase in the left ventricular end diastolic diameter. They felt that after the ablation of the obstruction in the LVOT there is a time related regression in left ventricular hypertrophy with a functional systolic and diastolic improvement. Some patients however did develop late congestive heart failure, but Merrill’s series yielded superb results from this surgical treatment of hypertrophic obstructive cardiomyopathy.

McCully and associates, from the Mayo Clinic, from their series of 47 patients identified a profile of patients that they felt clearly benefited from septal myectomy [76]. The profile included patients with asymmetric hypertrophy, severe systolic anterior motion of the mitral leaflets, and prolonged isovolumetric relaxation time. Spirito felt that patients who had both a large outflow gradient (50 mm of Hg or more) and severe symptoms of heart failure that were unresponsive to medical treatment were candidates for surgery [73]. Surgery abolishes or substantially reduces a basal outflow gradient in more than 90% of patients. Published data on about 1,500 patients from North American and European centers revealed substantial and persistent symptomatic improvement in about 70% of patients five years or more after surgery [77]. In centers with extensive surgical experience the operative mortality was less than 2%, but was higher in elderly patients, and in patients undergoing myotomy-myectomy and coronary artery bypass grafting [78-83].

Non-Surgical Techniques for Relief of LVOT
Spencer and associates have championed the non-surgical septal reduction therapy as an alternative treatment to surgical myotomy-myectomy. In 1998, Lakosis, Spencer and associates described the injection of 2 - 5 ml of alcohol down the septal branches of the left anterior descending artery [84]. This caused myonecrosis (a mean CK rise of 1,964 units) and all 33 symptomatic patients achieved significant relief of symptoms. Echocardiography at six weeks showed a 28% reduction in septal thickness, and 17% reduction in LV mass. Myocardial perfusion imaging showed a “septal amputation” pattern with scarring in the upper and middle septal areas [84]. In 2001, Nagueh compared the outcomes in 41 consecutive NSRT patients at Baylor College of Medicine with an age and gradient matched septal myomectomy cohort of patients at the Mayo Clinic [85]. No concomitant cardiac procedures were performed in the surgical cohort. There was one death in the NSRT cohort due to dissection of the LAD and at one year both groups had similar improvements. After septal myectomy more patients were maintained on medications and there was a higher incidence of mild aortic regurgitation. After NSRT there was a high incidence of permanent pacemaker implantation because of complete heart block (22% in the NSRT cohort versus 2% in the surgical cohort) [85].

In the United States, surgical treatment of hypertrophic obstructive cardiomyopathy has usually been reserved for patients with a high resting gradient in the LVOT, and who have failed aggressive medical treatment. The surgical results of myotomy and myectomy have generally been good. However, the non-surgical septal reduction therapy is being refined, and is gaining momentum as an alternative therapy to myotomy and myectomy.

Conclusion
In the ninety years since Tuffier performed the first aortic valve reconstruction, much has happened in the world of cardiovascular surgery. The development of vastly improved systems for cardiopulmonary bypass, as well as the universal use of myocardial protective techniques has resulted in impressively low mortality and morbidity statistics for patients undergoing cardiopulmonary bypass and aortic valve reconstruction 90 years after Tuffier's visionary work. No matter what the pathologic process involving the aortic valve is, the modern surgeon has a documented, effective set of reparative or replacement options to use today. Cardiologists and cardiac surgeons being emotional people, generally have very strong ideas about the most appropriate procedure to be performed on their patients. Thus, while a 45 year old patient with mixed aortic stenosis and regurgitation will receive a mechanical valve replacement in one part of the world, in another he might receive a Ross procedure, while in another part of the world he might receive an aggressive reparative procedure with a cusp extension. The good thing is that our specialty looks critically at the early and late outcomes of all aortic valve reconstructive procedures (and indeed for all cardiac surgical procedures) and these outcomes will help shape our recommendations for individual patients in the decades ahead.

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