Controversies in Our Current Decade Surrounding the Management of the Adult with Congenital Heart Disease

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Abstract

Heart defects occur in 75 of 1,000 live births, 25 % of which are at least moderate in severity. Less than 33 % of infants born with congenital heart disease 50 years ago survived to adulthood. With current advances in pediatric cardiology and surgery, it is now estimated in developed countries that up to 95 % are expected to reach adulthood. As life expectancy improves, the population of adults with congenital heart disease continues to grow. For the first time, it is now estimated that the number of adults with congenital heart disease has surpassed the number of children with congenital heart disease. While this is a remarkable achievement in the field of medicine, it is now apparent that early surgical interventions were reparative and not curative. Adults with congenital heart disease are increasingly requiring medical services and late complications are becoming increasingly apparent. As result, healthcare systems are now challenged to meet the demands of this complex and largely underserved population. This chapter discusses and highlights some of the important advances and controversies in the modern era in the management of the adult with congenital heart disease.

Keywords

ACHD • Adult with congenital heart disease • CHD • Complications • Congenital heart disease • Controversies • Healthcare • Medical services

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Introduction

Epidemiologic studies suggest that heart defects occur in 75 of 1000 live births, 25 % of which are at least moderate in severity. Less than 33 % of infants born with congenital heart disease 50 years ago survived to adulthood. With current advances in pediatric cardiology and surgery, it is now estimated in developed countries that up to 95 % are expected to reach adulthood. As life expectancy improves, the population of adults with congenital heart disease continues to grow. For the first time, it is now estimated that the number of adults with congenital heart disease has surpassed the number of children with congenital heart disease. While this is a remarkable achievement in the field of medicine, it is now apparent that early surgical interventions were reparative and not curative. Adults with congenital heart disease are increasingly requiring medical services and late complications are becoming increasingly apparent. These complications may arise from hemodynamic or hypoxic stress, postoperative sequelae, residual defects, and acquired comorbidities. As result, healthcare systems are now challenged to meet the demands of this complex and largely underserved population. This chapter discusses and highlights some of the important advances and controversies in the modern era in the management of the adult with congenital heart disease.

Elective Pulmonary Valve Replacement for Severe Pulmonary Regurgitation in the Asymptomatic Patient

Physiological pulmonary valve regurgitation (PR) is a common finding in adults with normally structured hearts. Severe PR, however, is often the result of a prior surgical repair for various types of congenital heart disease. These include tetralogy of Fallot, congenital pulmonary stenosis, or in repair of congenital defects utilizing the Rastelli procedure. Commonly thought to be benign and well tolerated by the right ventricle (RV), various studies have demonstrated that the long-standing volume loading of the RV caused by severe pulmonary regurgitation can lead to a number of adverse effects that can significantly impact a patient's quality of life and survival.

Pathophysiology of Chronic Pulmonary Valve Regurgitation

Although significant PR may be seen in a variety of forms of repaired congenital heart disease, the effects of concomitant cardiac defects, cyanosis, or poor ventricular compliance may influence the RV's response to severe PR in various ways. Examining the RV response to isolated congenital pulmonary regurgitation (a rare form of congenital heart disease) is one way to assess the effects of chronic severe PR without the confounding effects of other pathology. In a review of 72 cases of congenital pulmonary valve incompetence, Shimazaki et al. found that only 6 % of patients had symptoms develop by the age of 20 years. By age 40, this number, however, had increased to 29 % and there were 3 deaths [1]. This study reinforces the concept that the RV can accommodate the significant volume overload of PR for a period of many years or decades; however, eventually the RV compensatory mechanisms fail, symptoms develop, and the risk of further morbidity and mortality increases.

The ability of the RV to adapt to the volume overload imposed by chronic, severe PR is influenced by the degree and duration of the PR and particular characteristics of the RV and pulmonary arteries [2]. These characteristics include the diastolic pressure gradient between the main pulmonary artery (PA) and the RV, the capacitance of the PAs, and the duration of diastole [3]. For example, at the time tetralogy of Fallot repair, the RV is hypertrophied and restrictive, the PA is often small with a low compliance, and the time in diastole is usually short due to high heart rates. These factors tend to limit the degree of PR. However, over time, the increase in RV stroke volume eventually leads to an increased diameter and capacitance of the PA; there is an increase

in RV compliance; and there is longer duration of diastole with the decreasing heart rate seen with aging. This process leads to a progressive increase in the degree of PR over time [3].

RV dilation due to severe PR may also dilate the tricuspid valve annulus and lead to significant tricuspid valve regurgitation. Tricuspid regurgitation may further add to the volume load on the RV and contribute to further dilation. RV dilation from volume overload has been associated with exercise intolerance, arrhythmias, and sudden cardiac death [4–6]. It has also been found to correlate with QRS prolongation. A QRS duration on a resting ECG of $\geq$180 ms has been shown to be a sensitive predictor of life-threatening ventricular arrhythmias [2, 7].

Need for Pulmonary Valve Replacement

Because of continued surgical and medical advances, there are an increasing number of adult congenital patients surviving into adulthood with severe pulmonary regurgitation and facing the effects of chronic volume overload on the RV. Because of the worsened morbidity and association with sudden cardiac death, many of these patients will undergo pulmonary valve replacement (PVR). Approximately 15 % of patients following tetralogy of Fallot repair will need PVR [4]. The perioperative mortality after PVR has been shown to be 1–4 % with a 10-year survival of 86–95 % [8]. PVR has been the treatment of choice for symptomatic patients. It has been shown to improve ventricular volumes, improve NYHA functional class [9, 10], stabilize the QRS duration, and in conjunction with intraoperative cryoablation, decrease the incidence of preexisting atrial and ventricular tachyarrhythmias [11].

Many adults with severe pulmonary regurgitation often report being asymptomatic. Unfortunately, for various reasons (fear of inducing complications related to their congenital heart disease or being given exercise restrictions earlier in life), many of these patients have learned to limit themselves. Although they may be able to perform their daily activities without difficulty, they often will be found to have poor exercise capacity when objective measures are used. The results of an exercise stress test can be useful in these patients who feel asymptomatic. The data obtained can objectively quantify a patient's exercise capacity and peak oxygen consumption. These results may indicate that a patient who feels asymptomatic may actually be functionally limited due to their heart disease.

The decision as to when to intervene on severe pulmonary regurgitation in the asymptomatic patient has been the subject of much controversy. In making this decision, one must have the knowledge of the natural history of severe pulmonary regurgitation and risk factors associated with poor clinical outcomes. The difficulty of balancing the risks posed by long-standing severe pulmonary regurgitation with the risks posed by surgical PVR and the lack of longevity of various bioprosthetic valves (possibly exposing the patient to multiple future surgeries) contributes significantly to this controversy.

When considering the timing of PVR in the asymptomatic patient, the physician's goals of intervention should include the reduction of RV size, its beneficial effect on the electrical instability and incidence of tachyarrhythmias [12], and improving the patient's overall prognosis. Given the association between RV dilation and eventual RV dysfunction with increased morbidity and mortality in patients with chronic volume overload caused by severe PR, the optimal time to perform PVR in the asymptomatic patient would seem to be prior to the point of irreversible RV damage. This irreversible damage may be due to scarring and fibrosis and prevent ventricular remodeling after PVR [9]. Therefore, this decision becomes an important balancing act of performing PVR prior to irreversible RV dysfunction and delaying the need for reoperation by not performing PVR too early.

Cardiac magnetic resonance (cMRI) is the current gold standard in assessing RV size and function due to its tomographic nature and three-dimensional reconstruction capabilities. The RV volumes are determined in post-processing analysis by tracing the contour of the RV

endocardium in contiguous ventricular short axis images in both systole and diastole. Each of these images is of a specified thickness, and the volumes of each short axis image are summed to reach the end-systolic and end-diastolic volumes. There are three issues related to tracing the contours that commonly arise that may lead to imprecision in tracing the RV endocardial borders. These include the lack of a clear border between RV outflow tract and main pulmonary artery, inclusion versus exclusion of RV trabeculations, and differentiation of the RV from right atrial blood pool at the atrioventricular junction [13]. Despite these potential limitations, when experienced cMRI clinicians perform the measurements, estimated RV volumes have good reproducibility. When two expert cMRI clinicians evaluated RV volumes in patients with congenital heart disease involving the RV, Walsh et al. found the variability for indexed RV end-diastolic volumes to be 3.2 % and 3.3 % for intra- and inter-observer comparisons, respectively [13].

cMRI is the focus of many studies evaluating the optimal timing of PVR. Although many of these studies included fairly small numbers of patients, the majority of these studies have demonstrated a size threshold at which the RV normalizes in size after PVR. Therrien et al. demonstrated that in 17 adults with repaired tetralogy of Fallot evaluated by cMRI before and after PVR, there was a significant decrease in RVEDVI of 163 ml/m^2 prior to PVR to 107 ml/m^2 after PVR, and that in no patients with a RVEDVI of $>$170 ml/m^2 or a RVESVI of $>$85 ml/m^2 prior to PVR were RV volumes normalized after surgery [14]. Dave et al. showed similar results. In this study, 39 patients had a valved conduit placed when the RVEDVI on cMRI exceeded 150 ml/m^2. Twenty-one of these patients had a cMRI 6 months postoperatively. Of the 21 patients who had a cMRI postoperatively, only 7 of these patients had normalization of their RVEDVI. These 7 patients' preoperative RVEDVI was significantly lower than the other 14 patients who had some improvement, but no normalization (170+/−21.1 ml/m^2 vs. 203.6+/−35.6 ml/m^2). Their data also showed that the group of patients who had the lower preoperative RVEDVI not only normalized their RVEDVI after PVR but also improved their LV ejection fraction, whereas the group with higher preoperative RVEDVI did not. The authors hypothesize that this is likely due to improved LV filling by restoring the septal shift toward the RV [15]. These studies are in concordance with a cMRI study performed in children, by Buechel et al., in which cMRI 6 months after PVR showed that the decreased RV volumes, RV mass, and normalization of RV volumes after PVR were related to the preoperative RVEDVI. They found that RV remodeling occurred when the RVEDVI was $>$150 ml/m^2, but none of the patients with a RVEDVI $>$200 ml/m^2 had normalization of their RV volume after PVR [16]. Van Straten et al. showed that in 16 patients who underwent PVR, their postoperative RVEDVI was significantly decreased compared to their preoperative RVEDVI (164.2 ml/m^2 to 112.7 ml/m^2), and their RVESVI decreased significantly after PVR from 93.7 ml/m^2 to 60.9 ml/m^2 6 months after PVR. There was also evidence of improved diastolic function late 22 months after PVR [17]. Finally, Vliegen et al. showed that in 26 adults after tetralogy of Fallot repair who underwent PVR for severe PR, there was a decrease in RV end-diastolic volume index (RVEDVI) from 166.8 ml/m^2 prior to PVR to 114.3 ml/m^2 after PVR, a decrease in RV end-systolic volume index (RVESVI) from 99 ml/m^2 prior to PVR to 66.3 ml/m^2 after PVR, and an increase in RV ejection fraction when corrected for regurgitation and shunting (25.2 % prior to PVR and 43.3 % after PVR) [18]. These studies demonstrate the importance of monitoring preoperative RV volumes by cMRI, as there seems to be a RVEDVI and RVESVI threshold after which the RV has irreversible damage, and its volume will not normalize after PVR.

Percutaneous Pulmonary Valve Implantation

Recently, percutaneous pulmonary valve implantation (PPVI) has become available and may be

an alternative to surgery for some patients [19]. In this procedure, the replacement valve is implanted through a catheter, which is inserted through the skin into the femoral vein and then advanced into the pulmonary artery [19]. This approach currently is used only in patients who have had previous treatment using an RV outflow tract conduit or a bioprosthetic valve. The procedure also is limited by available valve size, with patients previously treated with larger homografts or bioprosthetic valves often not being candidates [19–23]. Initial series of PPVI as treatment for pulmonary valve dysfunction show good short-term efficacy [19–23]. These series have shown that PPVI is associated with decreased RV systolic pressure, decreased RV outflow tract gradients, and decreased degree of pulmonary regurgitation. Importantly, PPVI has also been associated with improved RV volumes by cMRI as well as improved functional class as measured by cardiopulmonary exercise testing [19–23]. Unfortunately, at this point there is little evidence of long-term efficacy. This procedure is also associated with several well-recognized complications, particularly stent fractures. Other complications include bacterial endocarditis, valve migration, conduit rupture or tear, coronary artery compression, and complete heart block [20–23]. As the availability and experience with PPVI increases, the decision when to perform PVR in the setting of the asymptomatic patient with severe pulmonary regurgitation will likely also continue to evolve. Clearly, if multiple surgeries can be avoided and that this is a safe and durable option, its role in the treatment of pulmonary regurgitation will grow.

Summary

Because of the improving survival rates of children with congenital heart disease, there are an increasing number of adult congenital heart disease patients that live with severe PR. Longstanding, chronic, severe PR can be tolerated by the RV for years; however, eventually the volume overload can have deleterious effects on the RV leading to symptoms (exercise intolerance, progressive arrhythmias, and signs of RV failure), but the need and timing of PVR in asymptomatic patients has been the subject of controversy. Over the past decade, studies using cMRI to assess RV volumes and function have demonstrated that PVR improves RV size and function, but the RV's ability to remodel and normalize (thereby, hopefully, preventing some of the morbidities associated with a dilated RV) is dependent on pre-PVR volumes (such as RVEDVI). Because of the low operative mortality, and the advancements in PPVI, PVR based on RV volumes measured on CMR in asymptomatic patients is becoming a widely accepted practice in many large adult congenital centers. Future research may focus on advancements in imaging (such as echocardiographic strain and strain rate) that may better indicate the appropriate timing of PVR and whether the practice of PVR (both surgical and PPVI) impacts mortality. PPVI short-term efficacy is clear, but studies documenting long-term efficacy are still needed.

The Ross Procedure

The Ross operation, first performed in 1967, involves replacing the aortic valve with a pulmonary autograft (the patient's own pulmonary valve) and then reconstructing the right ventricular outflow tract with an aortic or pulmonary homograft [24]. This was first performed using the subcoronary technique in which the pulmonary sinuses of the pulmonary root are partially excised and the pulmonary valve was secured in the recipient's aortic root with two suture lines, one below and one above the aortic annulus, leaving the coronary artery orifices unobstructed [25]. Initially, the Ross operation did not gain support among surgeons. This was due to its technical complexity, early failure of the autograft due to its need to be adapted to the geometry of the native aortic root, and the need to replace the pulmonary valve with a homograft [26–28]. However, due to technical variations, the Ross operation gained popularity during the 1980s and 1990s. These variations included the aortic root

replacement technique, in which the aortic root is excised, the pulmonary root is sutured to the aortic annulus and ascending aorta, and the coronary arteries are reimplanted into the neo-aortic root [25]. The inclusion cylinder technique is similar to the aortic root replacement technique, but with this technique, the pulmonary root is placed inside of the aortic root [25]. With these variations in technique and potential advantages, such as low thrombogenicity and avoidance of anticoagulation, favorable hemodynamic profile, low endocarditis risk, and the potential for growth in children [24, 28], the Ross operation became the operation of choice for children and young adults who required aortic valve replacement in the 1980s and 1990s [29]. However, outcomes seen in some of the more recent long-term studies have caused some controversy regarding the Ross operation.

Mortality

Early, midterm and late survival rates for the Ross operation are excellent. Elkins et al. showed an operative mortality of 2.7 % [29], and Luciani et al. showed an in-hospital death rate of 1 % [27]. Sievers et al. demonstrated a 30-day mortality rate after the subcoronary technique of 0.6 %, and a 99 % survival at 1 year, 97 % at 5 years, and 94 % at 8 years [28]. Finally, David et al. found a survival rate at 15 years to be 96.6 % [25]. At the end of the first decade, the survival for patients after the Ross operation has been found to be similar to the general population. This is likely due to the low risk of valve- and cardiac-related deaths because of the autograft's hemodynamic and biological features [19]. Importantly, when the survival in adults patients who underwent the Ross operation (mean age 47.3 years) was compared to the survival achieved for a matched cohort of adults who underwent mechanical aortic valve replacement (mean age 48 years) with optimal self-management of anticoagulation therapy, there was no difference between the two cohorts at 10-year follow-up [30].

Autograft Dilation

Autograft root dilation is the most common adverse event late after Ross operation occurring in up to one-third of patients [31, 32]. In a study by Luciani et al., freedom from root dilation was 99 %, 65 %, and 42.8 % at 1, 5, and 7 years, respectively. Freestanding root replacement had significant increases at all aortic root levels with equalization of the sinuses, sino-tubular junction, and ascending aorta as an almost uniform finding, while the inclusion cylinder technique had reverse remodeling. Factors predictive of late root dilation were younger age, larger preoperative dimension of root, use of root replacement technique, absence of pericardial strip buttressing, and length of follow-up [33]. The presence of a bicuspid aortic valve has not been found to correlate with an increased risk for neo-aortic root dilation [33].

The dilation seen in the root replacement technique may be because the pulmonary root is intrinsically different than the aortic root. These structural differences include thickness of the media layer and the orientation and fragmentation of elastic fibers [32]. Structural changes in the neo-aortic root due to devascularization (causing ischemic injury) and subjection to systemic arterial pressures have also been noted. These include cystic medial necrosis, elastic fiber fragmentation, and deficiency of smooth muscle cells [28, 32].

Autograft dissection has been reported in the literature [31, 34]. The anastomotic suture lines of the autograft and the native aorta limit the extension of the dissection distally and proximally into the coronaries. Because the autograft is denervated, dissections can be painless. The time to intervene on a dilated root is not well described, but reoperation is generally indicated when the aortic dimension exceeds 55 mm, when there is moderate or severe valvular regurgitation, or in the presence of RVOT complications (such as homograft stenosis or regurgitation) [31]. The prevalence of root dilation and the possibility of rupture or dissection have caused some to advocate for a more aggressive approach by considering root replacement in the setting of

a severely dilated neo-aortic root. If the autograft valve is functioning well, valve-sparing root replacement has been described [31].

Valve Dysfunction

Aortic autograft valvular regurgitation has been reported to occur in 14 % of patients at 10 years after the Ross operation [27]. In a study by Elkins et al., the predicted numbers of patients with at least moderate autograft regurgitation increased from 3.3 % at 5 years to 7.9 % at 10 years and 21.5 % at 16 years in a cohort in which root replacement was performed in the majority of patients. Independent variables associated with the development of at least moderate aortic autograft regurgitation were time elapsed since operation, immediate postoperative regurgitation of grade 1 or higher, and the patient's age at the time of operation [35]. David et al. found a freedom from moderate or severe autograft regurgitation of 90 % at 15 years in a cohort in which the operative techniques of modified subcoronary implantation and aortic root inclusion were the primary techniques used. Preoperative regurgitation was the only predictor of late regurgitation [25]. Incidence of autograft dysfunction due to regurgitation affects a minority but increases over time and is more prevalent in patients with neo-aortic root dilation. This may be due to remodeling of the root, loss of the sino-tubular junction, and aortic sinus dilation [33].

Reoperation

The need for reoperation on the autograft after the Ross operation increases with time. In a study in which patients had the Ross operation using the root replacement technique, at 5, 7, and 10 years postoperatively, freedom from reoperation on the aortic autograft was 95 %, 80 %, and 75 %, respectively [36]. In a study of patients who had the subcoronary autograft and root inclusion procedure with 8-year follow-up, freedom from reoperation was 98 % at 7 years for the autograft and 97 % for the homograft [26]. David et al. found freedom from autograft reoperation to be 93 % at 15 years. The majority of these patients had the root inclusion and the modified subcoronary implantation techniques as their original operations [25]. In comparison, the median interval to reoperation of contemporary, stented aortic bioprostheses has been found to be 7.74 years in patients less than 40 years of age and 12.93 years in patients 40–60 years of age. Multivariable risk factors associated with reoperation following bioprosthetic aortic valve replacement were found to include age and concomitant coronary artery bypass grafting [37].

Reintervention on the RV outflow tract may also become necessary following the Ross operation. A study by Klieverik found the freedom from reoperation on the pulmonary homograft was 87 % at 13 years [38]. Pasquali et al. found that during a median follow-up period of 6.5 years (2.5–10.4 months), there was a 14 % rate of reintervention. Small RV outflow tract homograft size was the strongest predictor of RV outflow tract reintervention. Younger age at the time of the Ross was found to be a univariate predictor of RV outflow tract reintervention [39].

Summary

Since first performed in 1967, the Ross operation has gone through various modifications in technique which has led to resurgence in use. These three techniques each have advantages and disadvantages, and many factors are considered when deciding which technique is best for an individual patient. These include native aortic annulus diameter, presence of aortic regurgitation, and surgeon's preference. Because of the risk of autograft dysfunction and root dilation in patients with preoperative aortic regurgitation and root dilation, some now believe that the Ross operation is best suited for young adults with aortic stenosis and a normal aortic root size [25]. Studies have demonstrated that the Ross operation has excellent long-term survival and quality of life, but the potential for long-term

complications such as autograft dysfunction, root dilation, and reoperation (including pulmonary homograft intervention) exists. Therefore, it is clear that lifelong surveillance is necessary.

Stent Versus Surgical Repair of Coarctation of the Aorta in the Adult

Introduction

Coarctation of the aorta occurs in approximately 6–8 % of patients with congenital heart disease. Anatomically, coarctation of the aorta is typically a discrete stenosis of the proximal descending aorta. However, many anatomic variations exist, including long-segment stenosis and transverse arch hypoplasia. In addition to anatomic variation, clinical presentations can vary considerably. The majority of patients present in infancy or childhood with congestive heart failure, systemic hypertension, or a murmur. Adults most commonly present with systemic hypertension. Moreover, adult patients with native coarctation may have significant comorbidities, including bicuspid aortic valve disease, ascending aortopathy, left ventricular dysfunction, a vast network of collateral vessels, coronary artery disease, and intracranial aneurysms. Choice of optimal treatment for adults found to have a significant coarctation of the aorta is somewhat controversial due to a number of factors including anatomic variations of the coarctation as well as comorbidities [40].

Surgical Intervention

Surgical intervention for coarctation of the aorta has seen continuous refinement since first described by Drs. Crafoord and Nylin in 1944 [41]. Modifications of surgical techniques have included patch aortoplasty, end-to-end anastomosis, subclavian flap aortoplasty, interposition graft, and extra-anatomic bypass graft. Each technique has specific advantages, disadvantages, and long-term outcome profiles. The choice of procedure has depended on several variables, including the specific anatomy of the coarctation, the patient's age, the era, and the surgeon's preference.

The outcomes of surgical intervention for coarctation of the aorta have been well documented. Rothman reviewed 11 series, comprising 2,355 patients who underwent surgical repair between 1946 and 1994. The operative mortality in all series ranged from 3 % to 32 % [42]. Toro-Salazar and coworkers reported the outcome of 274 patients who underwent surgical repair between 1948 and 1976. Twenty patients (7 %) died in the immediate postoperative period [43]. Cohen et al. reported results for 646 patients who underwent surgical repair from 1946 to 1981. The perioperative mortality was 2.6 %, despite the early era in which many of the procedures occurred [44]. More recently, Forbes et al. reported no operative deaths in 72 patients who underwent surgical repair between June 2002 and July 2009 [45]. Difficulty arises in direct extrapolation of surgical results to the adult congenital patient since most large studies include infants, children, and adults. Estimated surgical mortality in the adult with coarctation in the current era is very low, probably about 1 %.

The long-term outcomes after surgical invention have been well described. Once again, Cohen et al. reported survival rates of 91 % at 10 years, 84 % at 20 years, and 72 % at 30 years. The 20-year survival rate was 91 % if surgery was performed by the age of 13 years and 79 % if surgery was at an older age. Of 571 patients with long-term follow-up, there were 87 late deaths at a mean age of 38 years [44]. In the Toro-Salazar and coworkers series, of the 252 survivors, 45 (18 %) died at a mean age of 34.4 years. The survival rate was 95 % at 10 years after surgery, 89 % at 20 years, and 82 % at 30 years. Mean age of the 252 survivors at follow-up was 40 years [43]. In both studies, causes of late mortality included coronary artery disease, sudden death, heart failure, stroke, and ruptured aortic aneurysm.

Catheter Intervention

More recently, transcatheter intervention has been successfully utilized to treat native coarctation. Balloon angioplasty was first described by Singer et al. in 1982 [46]. The addition of intravascular stenting to balloon angioplasty gained acceptance throughout the 1990s. Currently, a combination of balloon angioplasty and stent placement is considered the treatment of choice in most centers for recurrent coarctation following surgical repair. However, for the treatment of native aortic coarctation, controversy exists.

Initial trials comparing surgery to angioplasty for native coarctation demonstrated similar results when comparing mortality and immediate reduction in gradient. However, concerns remained for medium- and long-term complications of aneurysm and recoarctation. In 1993, Shaddy et al. compared balloon angioplasty and surgery results for treatment of native coarctation. On follow-up, aneurysms were seen only in the angioplasty group (20 %) and not in the surgery group (0 %). In addition, although not statistically different, the incidence of restenosis (peak systolic pressure gradient $\geq$20 mmHg) tended to be greater in the angioplasty group (25 %) than in the surgery group (6 %) [47].

In 2010, the Congenital Cardiovascular Interventional Study Consortium reported the results of the first prospective multi-institutional registry evaluating the short- and long-term effectiveness and safety of aortic coarctation stenting. A total of 302 patients were enrolled from 34 centers in the United States, Canada, Europe, and South America from 2000 through 2009. Aortic imaging was encouraged during the follow-up period to screen for late aortic wall injuries, with mean follow-up of 1.1 years and the longest follow-up being 4.8 years. Patients were distributed among native (55 %) and recurrent (45 %) coarctation, with a mean age of 15 years. There were no deaths associated with the procedure. Adverse events were reported in 5 % of the patients and included aortic wall complications, balloon rupture, stent migration, stent fracture, and femoral artery injury. No adverse event required surgical intervention. Overall, this study confirmed the short- and long-term safety and effectiveness of coarctation stenting for the treatment of native and recurrent coarctation of the aorta [48].

The first multicenter observational study evaluating acute and follow-up outcomes of surgery, stenting, or balloon angioplasty for the treatment of native coarctation of the aorta in children, adolescents, and adults was published by the Congenital Cardiovascular Interventional Study Consortium in 2011. Between June 2002 and July 2009, 350 patients from 36 institutions were enrolled: 217 underwent stent placement, 61 underwent balloon angioplasty, and 72 underwent surgery. All three arms showed significant improvement acutely and at follow-up in resting systolic blood pressure and upper to lower extremity systolic blood pressure gradient. Stent placement was superior to balloon angioplasty in reducing upper to lower extremity systolic blood pressure gradient acutely. Surgery and stent placement were superior to balloon angioplasty at short-term follow-up in reducing the upper to lower extremity systolic blood pressure gradient. Stent patients had shorter hospitalization than surgical patients (2.4 vs. 6.4 days) and fewer complications than surgical and balloon angioplasty patients (2.3 %, 8.1 %, and 9.8 %, respectively). The balloon angioplasty patients were more likely to encounter aortic wall injury, both acutely and at follow-up. Almost 44 % of patients treated with balloon angioplasty developed an aneurysm or dissection within 5 years of treatment. Overall, complication rates at 60 months follow-up were 25.0 % for surgery, 43.8 % for balloon angioplasty, and 12.5 % for stenting. Unplanned reintervention procedures were necessary in 5.5 % of the surgical group, 6.5 % of the balloon angioplasty group, and 4.1 % of the stent group. However, 16.1 % of the stent group had planned reinterventions, which were performed either because of a staged approach or secondary to patient somatic growth. Overall, this study demonstrates that stent patients had significantly lower acute complications compared with surgery patients or balloon angioplasty patients, although they were more likely to

require a planned reintervention. At short- and intermediate-term follow-up, stent and surgical patients achieved superior hemodynamic and aortic arch imaging outcomes compared with balloon angioplasty patients [45].

Recently, covered stents have become available. Covered stents were first used in 1999 to treat a young adult male with a residual coarctation of the aorta and an associated aneurysm [49]. Since then, an array of covered stents have become available for clinical use and include the covered Cheatham-Platinum (CP) stent (NuMED, Inc., Hopkinton, NY), the Jomed covered stent (Jomed International AB, Helsingborg, Sweden), the Advanta stent (Atrium Medical Corporation, Hudson, NH), the Braile stent (Braile Biomedical, São José do Rio Preto, Brazil), and various stent grafts [49]. Covered stents offer the advantage of excluding any stretch-induced wall trauma from the endoluminal aspect of the aorta, particularly in the catastrophic event of aortic rupture which has been reported [49]. Some covered stents (i.e., CP covered stent) have rounded edges that are considered less traumatic to the native vessel.

Covered stents are most commonly employed as a rescue treatment in patients with aneurysms, acute dissection, localized rupture, and bare-metal stent-related complications. Covered stents have also been used as primary treatment in patients with complex anatomy: long-segment coarctation, near interruption, tortuous aortic arch, or advanced age defined as >30 years of age. Over the past decades, there have been several studies on the use of the covered stent in the treatment of coarctation of the aorta [50–52]. The largest study to date has been the study by Tzifa et al. In this study, 33 covered stents were placed in 30 patients. The mean age of the patients was 28 years (range 8–67 years); by computed tomography or magnetic resonance imaging, all stents were patent and were in good position 3–6 months following implantation [50].

While the use of covered stents has gained widespread acceptance in other countries, the device has not been approved in the United States. As a result, novel approaches like applying a Gore-Tex covering to a bare-metal stent have been reported when covered stents were unable to be used [49]. There are currently two large studies underway in the United States designed to assess the use of the CP stent for the treatment of CoA. The first, entitled the Coarctation of the Aorta Stent Trial (COAST), is charged with evaluating its use in patients weighing at least 35 kg. The second study, COAST II (Covered Cheatham Platinum CP Stents for the Prevention or Treatment of Aortic Wall Injury Associated with Coarctation of the Aorta), addresses patients with clinical situations that pose a high risk of aortic wall injury during bare-metal stenting. These include extreme narrowing, genetic aortic wall weakness, and advanced age. Patients with nearly atretic descending aorta 3 mm or less in diameter, acute or chronic aortic wall injury (i.e., descending aorta aneurysm/pseudo-aneurysm, contained aortic wall rupture, and non-contained rupture of the aortic wall), advanced age (men and woman aged 60 years or older), and genetic syndromes associated with aortic wall weakening, such as Marfan Syndrome, Turner Syndrome, familial bicuspid aortic valve, and ascending aortic aneurysm, are included. Patient enrollment for both of these trials is completed and preliminary results are expected to be published in the near future [49].

Summary

With greater than 6 decades of experience with treatment of aortic coarctation, the optimal therapy continues to evolve. The studies clearly demonstrate that the mortality for treatment of coarctation of the aorta appears to be very low (<1 %) and comparable among surgical, balloon angioplasty and stent interventions. Additionally, acute relief of obstruction appears to be similar, but slightly favoring stent therapy. Unfortunately, comparison of intermediate- and long-term outcomes continues to be difficult. Long-term outcomes in surgical patients are currently measured in decades, whereas catheter-based long-term outcomes are measured in years. In addition, the modality of follow-up has

changed over the years and makes comparison difficult. Early surgical patients were followed clinically without routine imaging. Currently, greater emphasis is placed on follow-up imaging especially within the catheter-based intervention cohort. Furthermore, it is evident that with longer follow-up, regardless of technique, a risk for sequelae exists, including systemic hypertension, aortic aneurysms, recoarctation or stenosis, aortic valve disease, and risk of endocarditis or endarteritis. Finally, whether covered stents will limit these sequelae and what their role will be in the future remains unknown.

Conclusion

Increasing numbers of CHD patients are now surviving to adulthood. Although early interventions have transformed the outcome for these patients, many of them have ongoing problems that require tertiary cardiac care in adult life. Numerous studies over the past decade have increased our understanding of repaired congenital heart defects and have deepened our appreciation of potential late complications. The purpose of this chapter was to review three controversial topics in our current decade surrounding the management of the adult with congenital heart disease. By no means are these the only controversies in our current era. They only serve as examples and emphasize the need for continued research in the management of this complex group of patients in efforts to offer future therapy that can be tailored to the individual needs of the adult with congenital heart disease.

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