

# Coarctation of Aorta: Review of Current Status of Surgical Correction

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**Abstract** Coarctation of Aorta (CoA) remains the most common aortic arch abnormality in children. Key to optimum management of these patients is early detection and timely intervention. Various surgical and transcatheter options are available for management of CoA. Based on the arch anatomy, site of coarctation and age of the patient various surgical options are available. These techniques include end-to-end anastomosis, extended end-to-end anastomosis, subclavian flap repair, interposition graft, and coarctation resection with prosthetic patch augmentation to mention a few. Careful literature review showed that, vast majority of surgeries for CoA in the current era include end-to-end and extended end-to-end anastomosis. Patch augmentation has gone out of favour due to high incidence of aneurysm formation. In theory, subclavian flap repair allows for tension-free repair using autologous tissue and avoids a circumferential suture line decreasing chances of recoarctation. But it does leave residual ductal and coarctation tissue increasing the risk of re-coarctation in future. Further subclavian flap repair compromises limb development but does not repair perceptible functional limitations. Treatment options should be individualised for each patient based on associated factors. Lifelong follow-up is mandatory for these patients to monitor for any late complications. Additionally, according to more recent literature, there has been a trend towards increased use of median sternotomy to repair isolated coarctation with hypoplasia of the aortic arch. This has been associated with a reduced rate of re-intervention in recent years. A midline sternotomy approach in coarctation with borderline transverse arch dimensions may give better long-term outcomes.

**Keywords** Coarctation of aorta, End-to-end anastomosis, Extended end-to-end anastomosis, Aortoplasty, Congenital heart defects

## 1. Introduction

The incidence of congenital heart disease (CHD) including even trivial lesions is approximately 75-81/1000 live births while the incidence of CHD requiring postnatal expert management is 2.5-3.0/1000 live births [1] [2].

Congenital anomalies of the aortic arch occur due to mal-development and involution of the six pairs of arches that arise from the paired dorsal aortae [3]. An anomalous development or insufficient increase in blood flow through the aorta can lead to a variety of aortic arch abnormalities that are frequently associated with other types of CHD [4]. Coarctation of the aorta is a well-known and studied congenital condition, which is typified by a narrowing of the descending aorta typically located at the aortic isthmus or the insertion site of the ductus arteriosus distal to origin of left subclavian artery. Aortic coarctation comprises 6-8% of CHD with an incidence of 4/10,000 live births [1] [3]. It has

a male preponderance and is frequently associated with other cardiac anomalies such as a bicuspid aortic valve, transposition of the great arteries, ventricular septal defect and patent ductus arteriosus.

Giovanni B Morgagni (1682 – 1771) an Italian anatomist and the professor of anatomy at the University of Padua was first who described the narrowing of the proximal descending aorta in an autopsy [5]. Few years later Meckel and Paris more elaborately explained the CoA physiopathology [6]. For the first time they examined the hemodynamic impact of CoA on the heart as well as body vasculature. The initial attention and exploration of CoA was not focused on symptomatic neonates who were exposed to a high risk of mortality. It did not take long for early intervention to be recognized as the gold standard treatment of CoA in neonates. Clarence Crafoord (1899 – 1984) a Swedish surgeon was the first who performed CoA repair in Sabbatsberg Hospital in Stockholm [7]. The patient was an 11-year old male patient who underwent resection of coarctation with an end-to-end anastomosis in October 1945. The operation revolutionised the surgical management of coarctation which previously was limited to animal experiments. Seven years later Lynxwiler and his team

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Received: Jun. 24, 2022; Accepted: Jul. 12, 2022; Published: Jul. 20, 2022

Published online at <http://journal.sapub.org/ajmms>

performed the first operation on a neonate through left thoracotomy with satisfactory results [8]. The operation performed by Lynxwiler was reproducible and soon became the main approach for the surgical management of CoA which is still currently practised.

Hypoplastic aortic arch and pseudocoarctation of the aorta are two lesser known aortic anomalies that may be mistaken for the better known lesion of coarctation. This misdiagnosis may lead to unnecessary anxiety for the patient and their families, while adding cost and possible harm from unnecessary invasive investigations. Gradual tapering of the distal aortic arch and isthmus is a normal finding in the first 3 months of life. Persistence of this stricture later on is pathologic [9]. The proximal arch segment is defined as hypoplastic when its external diameter is less than 60% of that of the ascending aorta. The corresponding limit for hypoplasia in the distal arch is 50%, and for the isthmus the limit is 40% [4]. The term *tubular hypoplasia* refers to a combination of abnormal small diameter and increased length (>5 mm in infants) between the segments of the aortic arch [10]. Hypoplastic arch is mostly seen in the paediatric age group and has rarely been reported as an isolated finding. Hypoplastic aortic arch may be seen in as many as 81% of patients with coarctation of the aorta [11] or may occur in association with other congenital anomalies such as tetralogy of Fallot [12], ventricular septal defect [13], and pulmonary artery sling [14]. Both coarctation and hypoplastic aortic arch are thought to be part of the same disease spectrum with pathological association between the coarctation and tubular hypoplasia of the transverse arch. Both conditions may cause hypertension proximal to the obstruction; other symptoms and hemodynamic findings will depend on the presence of effective collateral circulation around the obstructed aortic segment.

The third anomaly, pseudocoarctation of the aorta, consists of an elongated arch with a kink at the level of the isthmus. It does not cause obstruction to blood flow but can be associated with other congenital anomalies, including coarctation of aorta [15].

We identified a few cases of pseudocoarctation in the published literature. There were equal numbers of males and females with a mean age of 43 years. Ten (55%) patients presented with hypertension, three (17%) with dyspnea and two (11%) presented with back pain due to dissection of aorta. One patient had dysphagia due to compression of the esophagus by an enlarged aorta. Two (11%) patients were asymptomatic and diagnosed incidentally during CT imaging of the chest. Palpitations, syncope and chest pain were also reported by a few patients at the time of presentation [16]. Among the hypertensive patients, 40% had unequal blood pressure in the extremities [17]. Pseudocoarctation has been shown to be complicated by aneurysm formation of the thoracic descending aorta leading to sudden aortic rupture or aortic dissection [18].

Based on the arch anatomy, site of coarctation and age of the patient various surgical options are available. These

techniques include end-to-end anastomosis, extended end-to-end anastomosis, subclavian flap repair, interposition graft, and coarctation resection with prosthetic patch augmentation to mention a few.

## 2. Resection and End-to-end Anastomosis

Crafoord and Nylin [19] reported the first successful resection of coarctation of the aorta with end-to-end anastomosis. Their two patients were a 12-year-old boy and a 27-year-old man operated on in October 1944. Kirklin and associates [20] described the successful surgical treatment of coarctation of the aorta in an infant when they operated on a 10-week-old child performing successful coarctation resection with end-to-end anastomosis (and ligation of the left subclavian artery) in 1951.

Although the mortality rate was very acceptable in large series [21] several institutions reported a relatively high recoarctation rate (20–86%) particularly in the age group <1 year [22]. This high rate of stenosis in retrospect is attributed to: 1) the use of silk sutures instead of the currently available fine monofilament suture; 2) inadequate resection of all ductal tissue, which may extend into areas of normal-appearing aorta; 3) lack of growth at a circumferential suture line; and 4) lack of growth of a hypoplastic transverse arch. More recent series [23] [24] tend to indicate that with modern sutures and microvascular techniques, the recoarctation rate is reduced. Brouwer *et al.* [23] reported that, recoarctation rate in 53 infants (younger than 2 years) was 21%, while Quaegebeur *et al.* [24] stated this as 17%. However, this technique does not address the issue of a hypoplastic transverse arch, which is present in many infants.

## 3. Prosthetic Patch Aortoplasty

Chiefly because of the high rate of recoarctation with the classic end-to-end anastomosis technique, the technique of prosthetic patch aortoplasty was introduced. Vosschulte [25] in 1957 described an “isthmus plastic” procedure that developed into the prosthetic patch aortoplasty. For many years this was procedure of choice for older children (1–16 years of age) in several centers [26].

The prosthetic patch technique offers several advantages over simple resection with end-to-end anastomosis, 1) the collateral vessels are all preserved and do not require ligation and division; 2) the technique allows simultaneous enlargement of isthmus hypoplasia if necessary; 3) the anastomosis is tension free; 4) the posterior aortic wall and even a hypoplastic aortic arch will grow after prosthetic patch repair [27]. The primary worrisome late complication of this technique is aneurysm formation of the posterior aortic wall opposite the patch [28] [29]. This may be explained by several different factors. Most reported

aneurysm formation occurred after resection of the coarctation membrane with violation of the intimal layer. The patch causes altered hemodynamics arising from the different tensile strengths of the prosthetic patch and the posterior aortic wall, the pulsatile waveform being completely directed to the posterior aortic wall by the inflexible anterior patch [30]. In a collected series [26] [27] of 815 patients, 9% had recoarctation and 4% had aneurysm formation.

#### 4. Subclavian Flap Aortoplasty

The subclavian flap aortoplasty technique was introduced by Waldhausen and Nahrwold [31] in 1966. They reported successful coarctation repair in three patients aged 4 months, 6 months, and 3 years.

The advantages of the subclavian flap technique include its simplicity, short cross-clamp time, avoidance of prosthetic material, easy anastomotic hemostatic control, and increased anastomotic growth owing to the use of an autogenous noncircumferential flap [32]. Until the late 1980s the subclavian flap repair was widely utilized as the method of choice for repair of coarctation of the aorta in infants and children under 1 year of age [33]. However, there are some significant disadvantages of this technique which have led to many centers abandoning it in the current era. It does leave residual ductal and coarctation tissue increasing the risk of recoarctation in future. Further subclavian flap repair compromises limb development but does not repair perceptible functional limitations [28]. On the other hand, there was evidence of amputation of a gangrenous arm after subclavian flap aortoplasty [34].

#### 5. Prosthetic Interposition Graft

The use of a prosthetic interposition graft was first described by Robert Gross [64] in 1951 when he used an aortic homograft as a replacement for a coarctation in a child with a long narrowed coarctation segment. In 1960 Morris, Cooley, DeBakey, and Crawford [89] described the use of a Dacron prosthetic interposition graft in 3% of 171 patients undergoing coarctation repair. Currently, prosthetic interposition grafts are recommended [35] for patients over 10 years of age, patients with an associated aneurysm, patients with complex long-segment coarctation, and selected patients with recurrent coarctation. It is also a useful technique if during a planned resection and end-to-end anastomosis it appears that the anastomosis will be under tension or the aorta requires further resection because of a thinned aortic wall secondary to post-stenotic dilatation.

The obvious disadvantage of the interposition graft is the developmental size discrepancy in the growing child, making the operation more applicable for older patients. Another consideration is the longer aortic cross-clamp time taken to perform two circular anastomoses.

#### 6. Resection with Extended End-to-End Anastomosis

In 1977, Amato [36] reported four infants with hypoplasia of the distal transverse arch who underwent a new technique of resecting the coarctation and performing an extended anastomosis under the left carotid artery. In 1986 Lansman and associates [37] reported a series of 17 infants operated on between 1977 and 1985 having resection with extended end-to-end anastomosis. Forty-seven percent of these patients had a hypoplastic distal aortic arch and isthmus.

Thomson et al. [38] reported a data about 191 patients, under 1-year-old, who underwent extended end-to-end anastomosis, with 5% mortality and 4.2% re-coarctation, while Kaushal et al. [39] reported 2% mortality and 4% re-coarctation rate in 201 infants.

Many surgeons now feel that this is the procedure of choice for the infant with coarctation. There are several advantages to this technique. All coarctation tissue with uncertain potential for future growth is completely resected. The left subclavian artery is preserved, avoiding potential left arm ischemia or growth disorders. The procedure addresses and corrects hypoplasia of the transverse arch, the distal aortic arch, and the aortic isthmus. The technique avoids prosthetic material, limits the potential for aneurysm formation, and preserves normal vascular anatomy [35].

#### 7. Transcatheter Balloon Angioplasty

Transcatheter balloon angioplasty for native CoA was first introduced in the early 1980s [40]. Goal of the procedure is to cause tear in the intima media by overstretching of the narrow vessel site. After this dilatation and creation of tear, aortic wall remodelling is expected to result in long-term resolution of CoA and prevent recoil [41]. Balloon angioplasty is a preferred option in older children. It is also a preferred choice in younger patients with recoarctation. At present time use of balloon angioplasty in neonates and young infants is mainly reserved in patients with associated ventricular dysfunction to get them stabilized for definitive surgical repair. Its utility as an initial intervention in this very young age group has fallen out of favor due to high recurrence rate and risk of vascular complications [42].

#### 8. Transcatheter Stent Implantation

Transcatheter stent implantation was introduced in the late 1980s and was widely accepted as a therapeutic measure for patients with CoA in the early 1990s [43]. This is a preferred treatment method for native and recurrent CoA in older children, adolescents and adults [44]. Results from the Congenital Cardiovascular Interventional Study Consortium (CCISC) and the Coarctation of Aorta Stent Trial (COAST) trials show that stent patients have a lower rate of acute complications compared to surgery and balloon angioplasty

cohort [45]. But they are more likely to require a planned reintervention for stent dilatation, especially when implanted in younger patients [45]. Acute complications after stent implantation include stent migration, stent embolization, “jailing” of blood vessels, and aortic dissection [45] [46]. Long-term complications include planned reintervention for stent dilatation, neo-intimal proliferation in the stent causing stenosis, stent fracture, and aneurysm [45] [46].

## 9. Discussion

Coarctation of aorta (CoA) is a discrete narrowing in the aorta causing obstruction to the flow of blood, and this usually requires surgical treatment. Careful literature review of more recent papers showed that, surgeons, from all over the world, are using several different methods of surgical treatment of coarctation of aorta with or without arch hypoplasia, and they report advantages and disadvantages of these methods.

For instance, Mery *et al* from Texas Children Hospital studied 343 patients from 1-day-old to 18-year old who all had their coarctation repaired via left thoracotomy [47]. The majority of this population underwent excision of coarctation completed by either EEEA or EEA. elaborate? Only 2% underwent the repair of coarctation with SF elaborate?? technique. Intra-operative mortality was 1% and all patients were neonates. Two patients from the older children's age category underwent coarctectomy with an interpositional graft due to a large coarctation. Four (1.1%) patients died intra-operatively however there was no mortality on follow-up. Surprisingly the most common complication was pneumothorax requiring chest tube insertion. This is a recognised and rather rare complication which occurs due to micro-injuries to the left lung while retracted by a swab or instruments. During the follow-up period 14 (4%) patients, all from the EEA group (not statistically significant) and mainly neonates at the time of surgery (not statistically significant) underwent re-intervention for re-coarctation.

Penn State Hershey Medical Cent ran a study to examine the long-term results of SF in neonates who underwent surgery between 1966 and 1991 [45]. A total of 55 patients were studied who comprised a heterogeneous population from which 71% of patients had complex concomitant congenital heart disease with significant hemodynamic implications. Therefore, the in-hospital mortality rate was as high as 12.7%. Ironically the lower long term survival in complex group versus simple (isolated) coarctation was not statistically significant on Kaplan-Meier curve (log rank = 0.07). Re-coarctation occurred in three patients from a total of 16 patients who presented with an isolated coarctation and underwent SF repair. All three patients underwent re-operation from which two patients did not survive.

One of the largest studies which exclusively studied the outcome of CoA repair with SF technique has been conducted by Royal Liverpool Children's NHS Trust [48]. In this study 399 patients were investigated retrospectively

with a median follow-up of 14 years. The main population were infants presented with CoA or CoA and coexisting anomaly with a median age of 22 days ranging from 3 to 49 days. SF technique has been used frequently in this institution particularly when the arch hypoplasia exists or is labelled as borderline. In patients who underwent only SF repair of CoA a mortality of 36 patients (10.6%) has been reported while in the complex group is more than double. During the follow-up out of 124 patients who remained alive and had undergone isolated CoA repair, 20 patients developed re-coarctation requiring reintervention. One of these patients did not survive the re-intervention and another patient developed re-re-coarctation at a later date during the follow-up. This gave a rate of 14.9%. re-coarctation for isolated CoA repair. The median age for intervention in the isolated CoA group was 33 months. Neonates showed a significantly higher rate of re-coarctation as compared to infants. Nearly a third of patients (28.8%) reported that they have noticed a disparity between the two arms from a muscular development point of view while 24.6% of patients reported a discrepancy in the length of two arms.

Paediatric surgeons and cardiologists from Royal Brompton hospital retrospectively examined the outcome of SF technique for CoA repair in 185 patients [49]. 41 patients (22%) were identified with arch hypoplasia. Early mortality was 3% (6 patients) and survival at 5 years was as high as 98% + 2%. Early mortality was significantly associated with arch hypoplasia. Although SF technique is the authors' approach of choice, there is no report of post-operative complications such as arm ischaemia as well as arm growth problems. During the follow-up period (median 6.2 years) the rate of re-coarctation has been reported at 65 (11 patients). Similar to other studies appraised in this Chapter the authors demonstrated that neonates have a significantly higher rate of re-coarctation as compared to infants. It is interesting that half of patients diagnosed with arch hypoplasia still remained hypoplastic. This finding confirmed further that this particular group of patients requires more advanced surgical treatment managing the arch hypoplasia other than simple EEA or SF techniques.

A 10-year experience in the management of 188 patients with CoA has been reported by Iranian congenital heart surgeons [50]. This study included patients under 14 year-olds. Patch repair of the coarctation was the dominant surgical technique which may represent the institutional preference between 1994 and 2004. The re-stenosis was defined as the pressure gradient of 25 mmHg or more across the repaired site which at follow-up identified a relatively large number of patients: 54 (29%); who later underwent catheterisation. Re-coarctation was confirmed in 19 (10.1%) patients who required either stenting or balloon dilatation. The highest recurrence rate of stenosis was observed in the patch aortoplasty group and the lowest was in patients who underwent SF repair of CoA.

Uchytel *et al.* [51] from “Brno Centre of Cardiovascular Surgery and Transplantation” in Czech Republic retrospectively studied 342 patients who underwent surgery

for CoA repair. Patch aortoplasty has been used widely for the repair of CoA via left thoracotomy while it is easy to perform the operation and extensive mobilisation or dissecting the major structures is not necessary in this technique. In the population three patients developed aneurysm in whom the age of surgery as well as the age of presentation was not specified. These three patients received a stent percutaneously. Ten patients developed recoarctation requiring re-intervention. Following an increased incidence of aortic aneurysm after patch aortoplasty with Dacron graft for CoA repair, paediatric surgeons from Netherlands reported their experience with Polytetrafluoroethylene (PTFE) in a more focused age group of patients with a long-term follow-up (Walhout 2003). The sample size was large including 262 patients who underwent either patch aortoplasty or EEA. In the patch group re-coarctation, late HTN and aortic aneurysm occurred in 30 (25%), 8 (6.7%) and 8 (6.7%) of patients respectively. In EEA group re-coarctation occurred in 19 (14%) with a rate of late HTN at 2.2% (N=3). No aortic aneurysm was observed in the EEA group. The authors have reported that the actuarial 15-year probability of freedom from aortic aneurysm after patch aortoplasty was 93% + 3.1%. A false aneurysm occurred four days after surgery while all other aortic aneurysms developed on the medial side of the aorta opposite the patch.

Younoszai et al from Paediatric Cardiology and Paediatric Cardiothoracic Surgery, University of California retrospectively studied the outcome of coarctation excision and end-to-side in 88 patients who underwent CoA repair [52]. The technique is similar to those of EEEA; however, in end-to-side technique the descending aorta is anastomosed to the inferior aspect of the arch almost in front of LCCA. Arch hypoplasia particularly when the pathology involves the proximal arch is a risk factor for the development of recoarctation after EEA operation. End-to-side anastomosis allows the surgeons to create a larger arch in diameter, although the length might be affected and become shorter in size. No early mortality was reported. One (1.1%) patient developed left phrenic nerve palsy requiring diaphragm plication and another patient (1.1%) developed postoperative chylothorax requiring prolonged conservative management with a chest tube thoracostomy. Similar to those of EEEA in which extensive dissection and mobilisation of major vessels is crucial the rate of chylothorax, left phrenic nerve injury as well as RLN injury was not higher than other techniques of CoA repair. Re-coarctation was defined as when “either the blood pressure gradient between the right arm and a leg was equal or more than 20 mmHg or the flow velocity in the proximal descending aorta was equal or more than 2.5 m/s”. By this definition 3 infants (5.5%) were diagnosed with recoarctation. Authors believed that incorporating the descending aorta into the mid-arch and tying off the distal arch zone is the main reason that the rate of re-coarctation remains low.

However, in another group of scientific papers, all methods of surgical correction of coarctation of aorta were compared.

One of the largest groups of patients who underwent surgical repair of CoA with a relatively long follow-up, was studied by Indiana University School of Medicine in the United States [53]. They retrospectively studied 1,012 patients with a median follow-up of 14.2 years ranging from 2 weeks to 44 years. Half of the patients presented with an isolated CoA, 215 with VSD and the rest with other complex congenital heart diseases. The dominant operations were EEA and then SF in children however in older patients and adults patch aortoplasty and interpositional graft was prevalent. Total mortality has been reported at 3% (32 patients). Recoarctation occurred in 117 patients (11.5%) from which 65 patients were re-operated. Surgical site aneurysm occurred in 9% of patients requiring re-intervention which necessitated re-operation. The majority of these patients had previously undergone patch aortoplasty. Patients with re-coarctation underwent re-intervention with a median of 4.8 years after initial surgery however the range of re-intervention time is as wide as one week to 33 years.

Adeeb et al from one of the largest paediatric cardiac surgery institutions in Malaysia reported their experience in surgical management of CoA [54]. In 11 years they retrospectively studied 114 patients who underwent surgery for CoA. Majority of operations were EEA and then SF; however, 20 patients underwent Dacron path augmentation and interpositional graft. Four adults and 9 patients older than 9-year-old were also included in the study group. Re-coarctation occurred in patients with the age of younger than 48month-old. The rate of re-coarctation in EEA, SF and interpositional grafts was 1.7% (2 patients), 2.6% (3 patients) and 0.8% (one patient) respectively. Although the type of surgery was not an independent risk factor for re-coarctation rate, neonates (age < 30 days) developed more re-coarctation as compared to other age groups. Authors claimed that significantly more comorbidities occurred in the EEA group than SF and other surgical techniques.

Omeje et al. [55] reported their experience in the management of CoA in children's University Hospital of Bratislava in Slovakia. In a decade 201 patients' medical records who presented with symptomatic CoA and underwent surgical correction were retrospectively reviewed. The mean age has been reported as 3.5 years with a range of 2-day-old to 18-year-old. The majority of operations comprised EEA (51%) and then patch aortoplasty or augmentation (22%). They also treated the CoA with SF (12%) and EEEA (12%) techniques. Re-coarctation occurred in 19 (10%) of patients. Majority of re-coarctations occurred in neonates and EEA group. Interestingly patients with patch augmentation did not develop any re-coarctation and this can be explained by the fact that older children underwent this surgical technique.

Corno et al conducted a retrospective study to evaluate the outcome of surgery for treating CoA with a long follow-up exceeding 30 years [56]. The authors retrieved the data of 104 paediatric patients who underwent CoA repair operation in their institution. The surgical technique included a wide

spectrum of operations over a thirty years' practice including: SF, EEA, EEEA, patch aortoplasty, end-to-end conduit interposition and LSA to descending thoracic aorta which the two latter are now obsolete in today's practice. EEA and SF techniques comprised 53.9% (N=56) and 14.4% (N=16) of population in paediatric patients respectively. Re-coarctation has not been defined in this study; while the peak pressure gradient across the repaired site of more than 20 mmHg was reported in 7 patients out of 91 paediatric patients at follow-up (7.7%). Statistical analysis confirmed that the EEA technique is superior to other techniques including the SF approach.

In one of the largest studies with long follow-up, congenital heart surgeons from Children's Memorial Hospital in Chicago examined the rate of re-coarctation after surgical repair of CoA in 271 patients [57]. In 40 years 69 (25%), 61 (22%) and 18 (6.6%) patients underwent EEEA, SF and EEA operations respectively. More than a third of the population underwent patch aortoplasty (43%, N=11). The institution had ceased usage of Dacron graft technique in 1978; however, was still using PTFE patch for repairing CoA. Paraplegia occurred in one patient (0.4%) whose operation was complicated after performing EEA. RLN injury was reported in 6 (2%) patients and chylothorax in four patients (1.5%). Three aortic aneurysms occurred in association with Dacron and PTFE aortoplasty and in one patient occurred after repairing CoA with SF technique. More patients who initially underwent EEA developed re-coarctation (33%) as compared to SF (20%) and EEEA (7%). Interestingly the rate re-coarctation in the patch group which is now obsolete was only 5% and this was statistically significant as compared to EEA. In neonates, SF vs. EEEA techniques, which were the majority of performed surgical techniques in this age group, were compared. Statistical analysis confirmed that the difference between the two techniques in causing re-coarctation was significant while there was 6.3 times higher risk of reoperation in the SF group.

In another group of scientific papers, complications of surgeries and possibly affective factors to results of surgeries were evaluated. Such:

The outcome of isolated CoA repair via left thoracotomy which was performed between 2005 and 2011 was investigated retrospectively at Utah Primary Children's Medical Centre [58]. The rate of re-coarctation was inversely proportional to the patient's weight, meaning LBW was an independent risk factor for future repair failure. The aortic dimensions including transverse arch, distal arch and arch diameter did not influence the occurrence of re-coarctation. The patients with small transverse arch as low as  $z = -2.8$  had successful repair with no re-coarctation. High sino-tubular junction (STJ) measurements were associated with a high risk of re-coarctation and this was the only parameter from the entire aortic measurements which was identified as an independent risk factor. The authors' explanation about this rather unusual finding was that STJ is a surrogate for proximal size of the aorta and when STJ is increased this means there is a considerable discrepancy

between the proximal and distal of the aorta where CoA is located. Therefore, distal of aorta and coarctation area may require more aggressive management during the repair to minimise the discrepancies.

Cardiologists at the Hospital for Sick Children in Toronto conducted a retrospective study to examine the outcome of CoA repair in a high risk group of neonates with LBW (Weight < 2.5 Kg) [59]. In this population 36 neonates were studied who had an overall survival of 76% which is lower than neonates with normal weight. Interestingly despite the small size of patient the predominant surgical intervention to repair the coarctation was EEA. Re-coarctation occurred in 5 patients (13.8%). It was demonstrated that aortic valve growth improved in the EEA group as compared to other surgical techniques. Interestingly, patients with smaller transverse arch after CoA repair with EEA technique showed more rapid trajectories of growth compared with patients who underwent CoA repair with other techniques. Then, it was concluded that in the management of CoA the attention should be focused on the entire aorta and not only the coarctation area.

Melbourne Royal Children's Hospital has reported the outcome of CoA repair in a high risk group of patients with LBW (weight < 2Kg) over a period of 15 years [60]. Twenty-four patients were identified who underwent CoA repair with predominantly the EEEA (13 patients) and then SF (9 patients) techniques. A high rate of phrenic nerve injury (16.6%, 4 patients) after surgery was reported which can be related to the small size of the patients. Two patients (8.3%) suffered from chylothorax requiring prolonged drainage and conservative management. No RLN injury was reported. Late mortality during the follow-up occurred in one patient (5%) who had an isolated coarctation repair. Re-coarctation was defined as a symptomatic patient with peak pressure gradient of 25 mmHg and more across the repaired site. Nearly a third of patients (29.2%) developed re-coarctation however 4 patients (16.7%) underwent re-intervention. No difference was observed between EEEA and SF groups regarding the mortality rate as well as the incidence of re-coarctation.

In one of the largely cited studies by The Children's Hospital of Philadelphia and University of Pennsylvania School of Medicine, the impact of patients' weight on the outcome of CoA repair has been examined [61]. During 90s 103 patients with a median weight of 3.3 Kg ranging from 1 Kg to 6.4 Kg underwent repair of CoA via left thoracotomy. Major operations were either EEA (62%) or SF (32%). Aortic diameters were measured at 4 main locations: 1- diameter of ascending aorta proximal to BCA 2- diameter of transverse arch between LCCA and LSA 3- aortic isthmus diameter 4- descending aorta diameter. Age and weight as continuous variables were significantly correlated to the diameter of ascending aorta and transverse arch. Follow-up exceeded 9 years. One patient (0.9%) died peri-operatively in the hospital and another patient did not survive during the follow-up. It was reported that re-intervention was performed in 15 (15%) patients in which the median peak

pressure gradient across the repair site was as high as 55 mmHg (range: 25 mmHg – 100 mmHg). Following Cox regression analysis, it was interesting to observe that weight or being premature is not an independent risk factor for re-coarctation; however, age of younger than 2-week-old was significantly correlated to the incidence of re-coarctation. Transverse arch and transverse arch / ascending aorta ratio was significantly associated with an increased risk of re-coarctation. In this study comparing two major surgical techniques SF vs. EEA did not show any difference in causing re-coarctation during the follow-up period.

Nowadays, surgeons often report about arch hypoplasia with coarctation and its surgical repair.

One of the most recent retrospective studies was conducted by Tulzer et al in Austria [62]. The focus of this study was on the outcomes of excision of coarctation tissue in patients with arch hypoplasia. The two techniques of EEA and end-to-side were analysed. The data for 183 patients younger than 12-month-old who were operated on in the past 17 years from 1996 was collected. Median sternotomy was performed for patients with more complex anomaly i.e. hypoplasia of proximal arch. All of the patients who had their operation via median sternotomy were placed on cardiopulmonary bypass (CPB). Interestingly the patients who had their coarctation repaired via median sternotomy developed less re-coarctation as compared to the patients who underwent left thoracotomy. It is apparent from authors' comment that repair of complex arch hypoplasia which may require CPB via median sternotomy were performed via thoracotomy in early years. In fact, this conclusion may not be applied to all coarctation repairs performed via thoracotomy.

Wood et al from Our Lady's Hospital for Sick Children from the Republic of Ireland presented one of the largest studies with a focus on the outcome of CoA repair in patients with hypoplastic arch [63]. In this population the difference in the used surgical technique with previously explained EEEA was a side-to-side anastomosis rather than an end-to-end in the latter. All patients underwent excision of the coarctation followed by an incision on the inferior arch extending beyond the origin of LSA up to the origin of LCCA. Then the transected descending aorta was spatulated to accommodate the extended arch incision with a side-side anastomosis. The retrospective review of medical records identified 181 patients who were later categorised into three groups as per pathology: 1- isolated CoA 2- CoA + VSD 3- Complex congenital heart disease coexisting with CoA. The age median was 13.5 days ranging from 1 to 300 day-old. Authors defined an arch as hypoplastic when the transverse arch diameter was less than 1mm per Kg plus one. By applying this definition 107 (59%) patients were identified with hypoplastic arch. Patients were followed up regularly in 3-month intervals and then yearly. Early total mortality was observed in one patient (0.5%) from the complex group. Re-coarctation was defined as a resting peak pressure gradient across the repaired site of greater than 20 mmHg. Four patients (2.2%) were identified with this definition

having re-coarctation. Three of these patients were infants with LBW as low as 0.85 Kg.

Sakurai et al. [64], from Birmingham Children's hospital, retrospectively reviewed data about 288 patients who underwent isolated repair for coarctation of the aorta between 1991 and 2010. They compared results of surgeries in two decade groups, 1991-2000 and 2001-2010 and used surgical methods, such as EEA, SF, and patch aortoplasty via thoracotomy; and direct anastomosis repair and Back wall anastomosis with patch repair via midline sternotomy. In fact, they started to use the last method after 2001. Between 1991 and 2000, ten patients (6%) underwent repair through midline sternotomy, increasing to 41 patients (36%) between 2001 and 2010. Overall early mortality was 1% and late mortality was 3%. There was a statistically higher re-intervention rate (16%) in the decade 1991–2000, compared to 5% in the period 2001–10 ( $P = 0.02$ ). In patients with hypoplastic arch, the midline approach has a lower re-intervention rate than thoracotomy ( $P < 0.001$ ). They stated that, there had been a trend towards increased use of median sternotomy to repair isolated coarctation with hypoplasia of the aortic arch. This has been associated with a reduced rate of re-intervention in recent years. A midline sternotomy approach in coarctation with borderline transverse arch dimensions may give better long-term outcomes.

## 10. Conclusions

CoA remains the most common aortic arch abnormality in children. Key to optimum management of these patients is early detection and timely intervention. Various surgical and transcatheter options are available for management of CoA. Based on the arch anatomy, site of coarctation and age of the patient various surgical options are available. These techniques include end-to-end anastomosis, extended end-to-end anastomosis, subclavian flap repair, interposition graft, and coarctation resection with prosthetic patch augmentation to mention a few. Vast majority of surgeries for CoA in the current era include end-to-end and extended end-to-end anastomosis. Patch augmentation has gone out of favor due to high incidence of aneurysm formation. In theory, subclavian flap repair allows for tension-free repair using autologous tissue and avoids a circumferential suture line decreasing chances of recoarctation. But it does leave residual ductal and coarctation tissue increasing the risk of re-coarctation in future. Further subclavian flap repair compromises limb development but does not repair perceptible functional limitations. Treatment options should be individualized for each patient based on associated factors. Lifelong follow-up is mandatory for these patients to monitor for any late complications. Additionally, according to more recent literature, there has been a trend towards increased use of median sternotomy to repair isolated coarctation with hypoplasia of the aortic arch. This has been associated with a reduced rate of re-intervention in recent years. A midline sternotomy approach in coarctation with

borderline transverse arch dimensions may give better long-term outcomes.

## REFERENCES

- [1] J. Hoffman and S. Kaplan, "The incidence of congenital heart disease," *J Am Coll Cardiol.*, no. 39, pp. 1890-1900, 2002.
- [2] M. Reller, M. Strickland, T. Riehle-Colarusso, W. Mahle and A. Correa, "Prevalence of congenital heart defects in metropolitan Atlanta, 1998–2005," *J Pediatr*, vol. 6, no. 153, pp. 807-813, 2008.
- [3] B. B. Keller, R. R. Markwald and J. B. Hoving, "Chapter 9: Molecular Development of the Heart," in *Hurst's The Heart*, New York, McGraw-Hill, 2011.
- [4] A. J. Moulaert, C. C. Bruins and A. Oppenheimer-Dekker, "Anomalies of the aortic arch and ventricular septal defects," *Circulation*, no. 53, pp. 1011-1015, 1976.
- [5] G. Morgagni, "De sedibus et causis morborum," *Epist XVIII*, vol. 6, 1760.
- [6] S. Jarcho, "Coarctation of the aorta," *Am J Cardiol.*, vol. 7, pp. 844-52, 1961.
- [7] J. P. Kvitting and C. L. Olin, "Clarence Crafoord: a giant in cardiothoracic surgery, the first to repair aortic coarctation," *Ann Thorac Surg.*, vol. 1, no. 87, pp. 342-346, 2009.
- [8] C. P. Lynxwiler, S. Smith and J. Babich, "Coarctation of the aorta; report of case," *Arch Pediatr.*, vol. 5, no. 68, pp. 203-7, 1951.
- [9] S. Y. Ho and R. H. Anderson, "Coarctation, tubular hypoplasia, and the ductus arteriosus: histological study of 35 cases," *Br Heart J.*, no. 41, pp. 268-274, 1979.
- [10] H. Matsui, I. Adachi, H. Uemura, H. Gardiner and Y. S. Ho, "Anatomy of coarctation, hypoplastic and interrupted aortic arch: relevance to interventional/surgical treatment," *Expert Rev Cardiovasc Ther*, no. 5, pp. 871-880, 2007.
- [11] S. Conte, A. Lacour-Gayet, A. Serraf, M. Sousa-Uva, J. Bruniaux and A. Touchot, "Surgical management of neonatal coarctation," *J Thorac Cardiovasc Surg.*, vol. 4, no. 109, pp. 663-675, 1995.
- [12] D. L. Morales, D. J. DiBardio, W. Vick, C. D. Fraser and E. D. McKenzie, "Tetralogy of Fallot and hypoplastic aortic arch: a novel perspective," *J Thorac Cardiovasc Surg*, 129 (6) (2005), pp. 1448-1450, vol. 6, no. 129, pp. 1448-1450, 2005.
- [13] J. Yang, X. Yang and D. Yi, "Pulmonary artery aneurysm and hypoplastic aortic arch," *Ann Thorac Surg.*, no. 87, p. e29, 2009.
- [14] E. Y. Lee, "MDCT and 3D evaluation of type 2 hypoplastic pulmonary artery sling associated with right lung agenesis, hypoplastic aortic arch, and long segment tracheal stenosis," *J Thorac Imaging.*, no. 22, pp. 346-350, 2007.
- [15] M. Yamada, H. Horigome and S. Ishii, "Pseudocoarctation of the aorta coexistent with coarctation," *Eur J Pediatr.*, no. 155, p. 993, 1996.
- [16] S. Shindo, M. Katsu, A. Kojima, M. Kobayashi and Y. Tada, "Thoracic aortic aneurysm associated with pseudocoarctation of the aorta," *Gen Thorac Cardiovasc Surg*, vol. 12, no. 50, pp. 520-522, 2002.
- [17] R. Tung and R. J. Siegel, "Aortic pseudocoarctation associated with a stenotic congenitally bicuspid aortic valve," *Am J Cardiol.*, no. 100, pp. 157-158, 2007.
- [18] J. S. Ikonomidis and R. C. Robbins, "Cervical aortic arch with pseudocoarctation: presentation with spontaneous rupture," *Ann Thorac Surg.*, no. 67, pp. 248-250, 1999.
- [19] C. Crafoord and G. Nylin, "Congenital coarctation of the aorta and its surgical treatment," *J Thorac Surg*, no. 14, pp. 347-361, 1945.
- [20] J. W. Kirklin, H. B. Burchell and D. G. Pugh, "Surgical treatment of coarctation of the aorta in a ten week old infant: report of a case," *Circulation.*, no. 6, pp. 411-414, 1952.
- [21] L. J. Harlan, D. B. Doty and B. Brandt, "Coarctation of the aorta in infants," *J Thorac Cardiovasc Surg*, no. 88, p. 1012, 1984.
- [22] G. Ziemer, R. A. Jonas and S. B. Perry, "Surgery for coarctation of the aorta in the neonate," *Circulation*, no. 74, pp. 125-131, 1986.
- [23] M. H. Brouwer, C. Kuntze and T. Ebels, "Repair of aortic coarctation in infants," *J Thorac Cardiovasc Surg*, no. 101, pp. 1093-1098, 1991.
- [24] J. M. Quaegebeur, R. A. Jonas and A. D. Weinberg, "Congenital Heart Surgeons Society: Outcomes in seriously ill neonates with coarctation of the aorta. A multiinstitutional study," *J Thorac Cardiovasc Surg*, no. 108, pp. 841-851, 1994.
- [25] K. Vosschulte, "Surgical correction of coarctation of the aorta by an "isthmusplastic" operation," *Thorax*, no. 16, pp. 338-345, 1961.
- [26] C. L. Backer, K. Paape and V. R. Zales, "Coarctation of the aorta. Repair with polytetrafluoroethylene patch aortoplasty," *Circulation*, no. 92, pp. 132-136, 1995.
- [27] R. M. Sade, F. A. Crawford and A. R. Hohn, "Growth of the aorta after prosthetic patch aortoplasty for coarctation in infants," *Ann Thorac Surg*, no. 38, pp. 21-25, 1984.
- [28] K. Ala-Kulju and L. Heikkinen, "Aneurysms after patch graft aortoplasty for coarctation of the aorta: long-term results of surgical management," *Ann Thorac Surg.*, no. 47, pp. 853-856, 1989.
- [29] M. Roth, P. Lemke and M. Schönburg, "Aneurysm formation after patch aortoplasty repair (Vosschulte): reoperation in adults with and without hypothermic circulatory arrest," *Ann Thorac Surg*, no. 74, pp. 2047-2050, 2002.
- [30] P. M. Clarkson, P. W. Brandt and B. G. Barratt-Boyes, "Clarkson PM, Brandt PWT, Barratt-Boyes BG, et al. (1985) Prosthetic repair of coarctation of the aorta with particular reference to Dacron onlay patch grafts and late aneurysm formation," *Am J Cardiol*, no. 56, pp. 342-346, 1985.
- [31] J. A. Waldhausen and D. L. Nahrwold, "Repair of coarctation of the aorta with a subclavian flap," *J Thorac Cardiovasc Surg*, no. 51, pp. 532-533, 1966.



- [32] A. L. Moulton, J. I. Brenner and G. Roberts, "Subclavian flap repair of coarctation of the aorta in neonates. Realization of growth potential?," *J Thorac Cardiovasc Surg*, no. 87, pp. 220-235, 1984.
- [33] J. C. Milliken, W. J. Brawn and R. B. Mee, "Neonatal coarctation: clinical spectrum and improved results.," *J Am Coll Cardiol*, no. 15, p. 78, 1990.
- [34] G. Mellgren, L. G. Friberg and B. O. Erikson, "Neonatal surgery for coarctation of the aorta. The Gothenburg experience.," *Scand J Thorac Cardiovasc Surg*, no. 21, pp. 193-197, 1987.
- [35] C. L. Backer and C. Mavroudis, "Coarctation of the aorta.," in *Pediatric Cardiac Surgery, 4th edition*, Philadelphia, PA, Mosby, 2014, pp. 840-844.
- [36] J. J. Amato, H. F. Rheinlander and C. J. Cleveland, "A method of enlarging the distal transverse arch in infants with hypoplasia and coarctation of the aorta," *Ann Thorac Surg*, no. 63, pp. 261-263, 1977.
- [37] S. Lansman, A. J. Shapiro and M. S. Schiller, "Extended aortic arch anastomosis for repair of coarctation in infancy.," *Circulation*, no. 74, pp. 137-141, 1986.
- [38] J. D. Thomson, A. Mulpur and R. Guerrero, "Outcome after extended arch repair for aortic coarctation," *Heart*, no. 92, pp. 90-94, 2006.
- [39] S. Kaushal, C. L. Backer and J. N. Patel, "Coarctation of the aorta: midterm outcomes of resection with extended end-to-end anastomosis," *Ann Thorac Surg*, no. 88, p. 1932-193, 2009.
- [40] M. I. Singer, M. Rowen and T. J. Dorsey, "Transluminal aortic balloon angioplasty for coarctation of the aorta in the newborn," *Am Heart J*, no. 103, p. 131-132, 1982.
- [41] M. Gewillig, W. Budts, D. Boshoff and G. Maleux, "Percutaneous interventions of the aorta," *Future Cardiol*, no. 8, pp. 251-269, 2012.
- [42] S. Fruh, W. Knirsch, A. Dodge-Khatami, H. Dave, R. Pretre and O. Kretschmar, "Comparison of surgical and interventional therapy of native and recurrent aortic coarctation regarding different age groups during childhood," *Eur J Cardiothorac Surg*, no. 39, pp. 898-904, 2011.
- [43] M. P. O'Laughlin, S. B. Perry, J. E. Lock and C. E. Mullins, "Use of endovascular stents in congenital heart disease," *Circulation*, no. 83, p. 1923-1939, 1991.
- [44] T. J. Forbes, D. W. Kim and W. Du, "Comparison of surgical, stent, and balloon angioplasty treatment of native coarctation of the aorta: an observational study by the CCISC (Congenital Cardiovascular Interventional Study Consortium)," *J Am Coll Cardiol*, no. 58, pp. 2664-2674, 2011.
- [45] E. E. Adams, W. R. Davidson, N. A. Swallow, M. J. Nickolaus, J. L. Myers and J. B. Clark, "Long-term results of the subclavian flap repair for coarctation of the aorta in infants," *World J Pediatr Congenit Heart Surg*, no. 4, pp. 13-18, 2013.
- [46] T. J. Forbes, D. W. Kim and W. Du, "Comparison of surgical, stent, and balloon angioplasty treatment of native coarctation of the aorta: an observational study by the CCISC (Congenital Cardiovascular Interventional Study Consortium)," *J Am Coll Cardiol*, no. 58, pp. 2664-2674, 2011.
- [47] C. M. Mery, F. A. Guzmán-Pruneda, J. G. Trost, E. McLaughlin, B. M. Smith, D. R. Parekh and I. Adachi, "Contemporary Results of Aortic Coarctation Repair Through Left Thoracotomy.," *Ann Thorac Surg*, vol. 3, no. 100, pp. 1039-46, 2015.
- [48] R. Pandey, M. Jackson, S. Ajab, G. Gladman and M. Pozzi, "Subclavian flap repair: review of 399 patients at median follow-up of fourteen years," *Ann Thorac Surg*, vol. 4, no. 81, pp. 1420-8, 2006.
- [49] M. Jahangiri, E. Shinebourne, D. Zurakowski, M. Rigby, A. Redington and C. Lincoln, "Subclavian flap angioplasty: does the arch look after itself?," *J Thorac Cardiovasc Surg*, vol. 2, no. 120, pp. 224-9, 2000.
- [50] M. G. Dehaki, A. A. Ghavidel, N. Givtaj, G. Omrani and S. Salehi, "Recurrence rate of different techniques for repair of coarctation of aorta: A 10 years experience.," *Ann Pediatr Cardiol*, vol. 2, no. 3, pp. 123-126, 2010.
- [51] B. Uchytíl, J. Cerný, J. Nicovsky, M. Bednarik, H. Bedanova, J. Necas, M. Osmerova and M. Haslingerova, "Surgery for coarctation of the aorta: long-term post-operative results.," *SCRIPTA MEDICA (BRNO)*, vol. 6, no. 76, pp. 347-356, 2003.
- [52] A. K. Younoszai, V. M. Reddy, F. L. Hanley and M. M. Brook, "Intermediate term follow-up of the end-to-side aortic anastomosis for coarctation of the aorta.," *Ann Thorac Surg*, vol. 5, no. 74, pp. 1631-4, 2002.
- [53] M. L. Brown, H. M. Burkhart, H. M. Connolly, J. A. Dearani, F. Cetta, Z. Li, W. C. Oliver, C. A. Warnes and H. Schaff, "Coarctation of the aorta: lifelong surveillance is mandatory following surgical repair.," *J Am Coll Cardiol*, vol. 11, no. 62, pp. 1020-5, 2013.
- [54] S. M. Adeeb, H. Leman, A. Sallehuddin, A. Yakub, Y. Awang and M. Alwi, "Coarctation of aorta repair at the National Heart Institute (1983-1994).," *Med J Malaysia*, vol. 1, no. 59, pp. 11-4, 2004.
- [55] I. Omeje, R. Poruban, M. Sagat, M. Nosai and V. Hraska, "Surgical treatment of aortic coarctation," *Images Paediatr Cardiol*, vol. 2, no. 6, pp. 18-28, 2004.
- [56] A. F. Corno, U. Botta, M. Hurni, M. Payot, N. Sekarski, P. Tozzi and L. K. von Segesser, "Surgery for aortic coarctation: a 30 years experience," *Eur J Cardiothorac Surg*, vol. 6, no. 20, pp. 120-26, 2001.
- [57] A. Dodge-Khatami, C. L. Backer and C. Mavroudis, "Risk factors for recoarctation and results of reoperation: a 40-year review.," *J Card Surg*, vol. 6, no. 15, pp. 369-77, 2000.
- [58] D. T. Truong, L. Y. Tani, L. L. Minich, P. T. Burch, T. R. Bardsley and S. C. Menon, "Factors associated with recoarctation after surgical repair of coarctation of the aorta by way of thoracotomy in young infants," *Pediatr Cardiol*, vol. 1, no. 35, pp. 164-70, 2014.
- [59] T. Karamlou, A. Bernasconi, E. Jaeggi, F. Alhabshan, W. G. Williams, G. S. Van Arsdell, J. G. Coles and C. A. Caldarone, "Factors associated with arch reintervention and growth of the aortic arch after coarctation repair in neonates weighing less than 2.5 kg.," *J Thorac Cardiovasc Surg*, vol. 5, no. 137, pp. 1163-7, 2009.
- [60] C. D. Sudarshan, A. D. Cochrane, Z. H. Jun, R. Soto and C. P. Brizard, "Repair of coarctation of the aorta in infants

- weighing less than 2 kilograms.," *Ann Thorac Surg.*, vol. 1, no. 82, pp. 158-63, 2006.
- [61] D. McElhinney, S. G. Yang, A. N. Hogarty, J. Rychik and M. M. Gleason, "Recurrent arch obstruction after repair of isolated coarctation of the aorta in neonates and young infants: is low weight a risk factor?," *J Thorac Cardiovasc Surg.*, vol. 5, no. 122, pp. 883-90, 2001.
- [62] A. Tulzer, R. Mair, M. Kreuzer and G. Tulzer, "Outcome of aortic arch reconstruction in infants with coarctation: Importance of operative approach.," *J Thorac Cardiovasc Surg.*, vol. 6, no. 152, pp. 1506-1513, 2016.
- [63] A. E. Wood, H. Javadpour, D. Duff, P. Oslizlok and K. Walsh, "Is extended arch aortoplasty the operation of choice for infant aortic coarctation? Results of 15 years' experience in 181 patients.," *Ann Thorac Surg.*, vol. 4, no. 77, pp. 1353-7, 2004.
- [64] T. Sakurai, J. Stickley, O. Stumper, N. Khan, T. Jones, D. Barron and W. Brawna, "Repair of isolated aortic coarctation over two decades: impact of surgical approach and associated arch hypoplasia," *Interact Cardiovasc Thorac Surg.*, vol. 5, no. 15, pp. 865-870, 2012.