Aortic Coarctation

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KEYWORDS

• Aortic coarctation • Congenital heart disease • Aorta • Aortopathy • Stent therapy

KEY POINTS

- Aortic coarctation is a discrete narrowing of the thoracic aorta and often associated with other forms of congenital heart disease.
- Invasive gradients greater than 20 mm Hg or mean gradient greater than 20 mm Hg by Doppler constitute indication for repair.
- Multimodality imaging is a major component of diagnosis and surveillance.
- Hypertension remains a significant morbidity even in the setting of successful repair.
- Lifelong surveillance by specialists in congenital heart disease is indicated to identify potential long-term complications.

INTRODUCTION

Aortic coarctation accounts for 6% to 8% of all congenital heart disease[1] and occurs with an incidence of 3 to 4 cases out of 10,000 live births with a male predominance of 2:1.[2] It is defined as a narrowing of the thoracic aorta, typically located at the insertion of the ductus arteriosus just distal to the left subclavian artery but can be located distant to the ductus as well. Aortic coarctation is often a discrete stenosis but can be long-segment and/or tortuous. Discrete coarctation can occur in isolation but is often associated with other congenital heart defects, including bicuspid aortic valve (60%), aortic arch hypoplasia and other arch anomalies (18%), ventricular septal defect (13%), mitral valve abnormalities (8%), subaortic stenosis (6%), among others.[3] Shone syndrome is a constellation of left-sided obstructive defects, including supramitral ring, parachute mitral valve, subaortic stenosis, along with aortic coarctation, which suggests a common developmental origin.[4]

The underlying cause of aortic coarctation is not fully elucidated but a genetic underpinning has been implicated. Several candidate genes have been identified, including NOTCH1,[5,6] MCTP2,[7] and FOXC1.[8] For example, NOTCH1 mutations have been identified in patients with other left-sided lesions, including bicuspid aortic valve and hypoplastic left heart syndrome. The high prevalence of aortic coarctation in Turner syndrome as well as PHACE, DiGeorge, and Noonan syndromes also support a genetic component to this condition.[9]

Aortic Coarctation: An Aortopathy

Morphologically, aortic coarctation is characterized by infolding of ductal tissue posteriorly composed of an intimal and medial component that can extend around the entire circumference of the aorta.[10] Under electron microscopy, the intimal component is laminated, staining for fibrin, with progressive thickening over time[11] and with alterations in smooth muscle cell phenotype.[12] Histologically, there is evidence of cystic medial necrosis and elastic fiber formation, which may form the basis of aortic dilation, aneurysm formation, and dissection in aortic coarctation.[13,14]

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Aortic coarctation is considered a diffuse aortopathy as demonstrated by abnormal histologic findings, impaired vascular properties, and inflammation. The pathophysiology of the aorta in coarctation is notable for endothelial dysfunction and abnormal elastic properties even after repair.[15–17] Cardiac magnetic resonance (CMR) imaging and vascular ultrasound studies in patients with aortic coarctation demonstrate reduced aortic distensibility, which is associated with higher central systolic blood pressure.[18,19] Circulating levels of proinflammatory molecules involved in atherogenesis are also increased.[17] Positron emission tomography/computed tomography with ^{18}F-fluorodeoxyglucose imaging of normotensive patients with repaired coarctation demonstrated vascular inflammation in the aorta.[20] A small open-label study on 34 young adults with repaired aortic coarctation demonstrated salutary effects of atorvastatin on vascular function and levels of proinflammatory cytokines and molecules.[21]

Natural History

Unrepaired, the natural history of aortic coarctation carries a dismal prognosis. A seminal study by Campbell in 1970 describes autopsy findings of 304 patients who survived beyond the age of 1 year. The mean age of death was 34 years with cause of death ascribed to congestive heart failure (25.5%), aortic rupture (21%), bacterial endocarditis (18%), and intracranial hemorrhage (11.5%).[22] The paper goes on to state "This poor outlook makes an operative mortality in the region of 5% a small price to pay for the greatly increased security afterward" reflecting a risk–benefit ratio highly favoring surgical repair.[22]

However, the prognosis for aortic coarctation after repair is not altogether benign. With evolutions in diagnosis and treatment, including transcatheter options, survival prospects have improved greatly but are still lower than the general population. Patients with aortic coarctation are at continued risk for morbidities delineated by Campbell and others, including heart failure, hypertension, recoarctation, aortic aneurysm/dissection, and sudden death.

CLINICAL PRESENTATION

The clinical presentation of native coarctation in the adult depends on the severity of the lesion. Hemodynamically, the increased afterload due to obstruction of flow from the left ventricle may be accompanied by significant hypertension in the aorta and branch vessels proximal to the coarctation site and may be associated with systemic ventricular dysfunction, vessel aneurysm formation, and effects of premature atherosclerosis. Distal to the coarctation, there is diminished flow, and collaterals may develop to supplement areas of relative hypoperfusion.

In patients without aortic obstruction, the aortic pulse should be transmitted at equal speed and intensity from the left ventricle to the radial and femoral pulses that are approximately equidistant from the left ventricle. In patients with significant aortic coarctation, pulse wave propagation is both slowed and diminished distal to the coarctation, thereby delaying and diminishing femoral pulse relative to radial pulse. Standard practice dictates that all pulses should be checked at least once in the evaluation of all patients with systemic hypertension to rule out significant aortic coarctation.[23] Four extremity blood pressures should be measured to assess for gradients, but may be misleadingly lower than expected in the setting of significant collateral formation.

Most adult patients are asymptomatic but can present with severe hypertension leading to headaches, epistaxis, heart failure, and/or aortic dissection. Collateral vessel formation around the coarctation when severe, may mitigate the severity of some of these symptoms (**Fig. 1**). **Table 1** summarizes the clinical presentation and physical examination of the adult presenting with aortic coarctation.

DIAGNOSIS AND IMAGING

Transthoracic Echocardiography

Transthoracic echocardiography is often the first-line modality to assess for suspected aortic coarctation due to familiarity and easy accessibility. It can also assess for left ventricular mass, both systolic and diastolic function, and other associated congenital heart lesions. Particular attention should be paid to examining left-sided structures (eg, mitral valve, papillary muscle architecture, left ventricular outflow tract, and aortic valve).

In the suprasternal long-axis, 2D as well as color and spectral Doppler can be used to localize the anatomy of aortic coarctation and estimate the degree of narrowing, but a number of caveats exist. The typical "saw tooth" continuous-wave Doppler appearance of severe coarctation (**Fig. 2**) representing peak systolic acceleration during systole and velocity decay during diastole is affected by aortic compliance. The absence of such may not always indicate mild degrees of coarctation.[24]

The modified Bernoulli equation has been used to calculate the peak instantaneous gradient across the coarcted segment, but many physiologic conditions can affect the accuracy of these estimations. Decompressing collaterals can decrease the peak systolic velocity across the

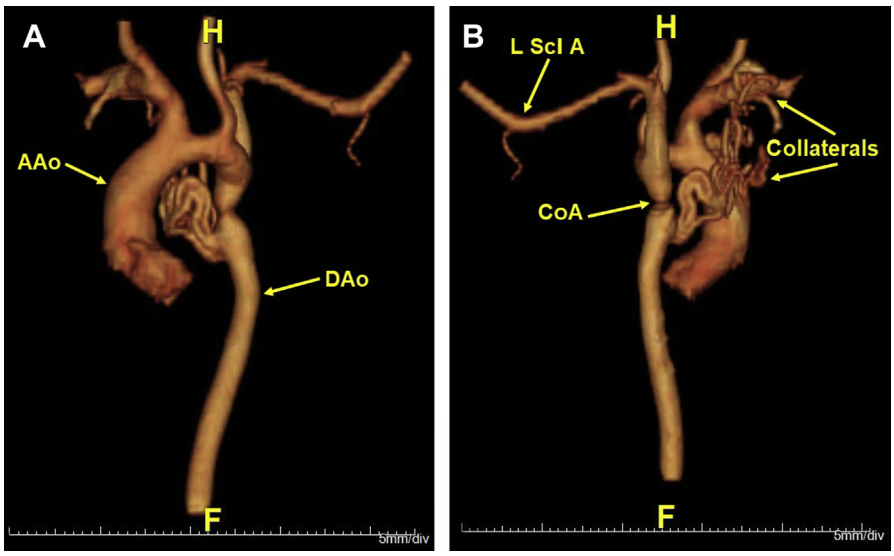

Fig. 1. Volume-rendered 3D reconstruction from a computed tomography of the aorta (*A*, anterior view; *B*, posterior view) in a 43-year-old man who presented to the emergency department with long-standing, poorly controlled hypertension. The study obtained demonstrates severe, native coarctation of the aorta in the presence of marked collateral formation. AAo, ascending aorta; DAo, descending aorta; L Scl A, left subclavian artery.

coarctation leading to underestimation of severity. Increased stiffness proximal to the narrowing increases the degree of proximal velocity acceleration resulting in overestimation of the gradient, even when using the expanded Bernoulli equation.[25] Long-segment stenosis and serial obstructions (ie, associated subaortic obstruction and/or supravalvar aortic stenosis) are also other conditions in which Doppler-derived gradients are less reliable.

Imaging of the aorta by transthoracic echocardiography, however, is often limited by body habitus and technique (**Figs. 3** and **4**). The mainstay of diagnosis and assessment of aortic pathology in the adult is advanced 3D imaging: computed tomographic angiography (CTA) and CMR imaging.

Cardiac Computed Tomographic Angiography

Cardiac CTA provides superior spatial resolution over other modalities, such as CMR and affords advantages in evaluation of vascular anatomy and aortic dimensions, morphology, and evaluation of the coronary arteries. It is the gold standard for imaging aortic dissection—a known complication of adult patients with coarctation, bicuspid aortic valve and especially those with aortic aneurysm.[26] For the adult who has undergone transcatheter intervention, it can also be used to assess luminal patency and is the preferred method to evaluate for long-term complications after stent therapy, including fracture, restenosis, or endoleak (**Fig. 5**). It is also the imaging modality of choice to evaluate the thoracic aorta in patients with contraindications to CMR, such as a pacemaker or defibrillator. The disadvantages of CTA include the use of ionizing radiation and intravenous dye and associated contrast-induced nephropathy. Fortunately, there have been significant advances in radiation dose reduction strategies, resulting in substantial reductions of total radiation dose for cardiac CTA.[27] This now provides cardiac CTA as a suitable imaging tool for the cardiologist providing care for this population of congenitally affected adults. Still, it is important to balance the risk–benefit ratio of radiation exposure in the young adult with congenital heart disease when considering this imaging modality.

Cardiac Magnetic Resonance Imaging

CMR, which includes MR angiography, is advantageous given its lack of ionizing radiation or risk of contrast-induced nephropathy. It not only affords excellent visualization of aortic anatomy by angiography (**Fig. 6**) but also provides quantitative data on biventricular volumes, mass, and systolic function. In addition, phase contrast flow sequences can be used to quantify velocity acceleration in either discrete coarctation or recoarctation, estimate shunt fraction to evaluate for associated intracardiac shunts, and detect collateral flow in the intercostal arteries.[28,29] The usefulness of CMR in this population has been thoroughly investigated. In a study of adult patients with coarctation referred for routine

Table 1
Clinical presentation and diagnosis of aortic coarctation

Symptoms	Headache Epistaxis Exertional intolerance Dizziness Lower extremity claudication Abdominal angina Intracranial hemorrhage Heart failure
Physical examination	Upper extremity hypertension Gradient between upper and lower extremity blood pressures Weak or absent femoral pulses Brachio-femoral delay Prominent, nondisplaced apical impulse Loud A2 Systolic ejection click and midsystolic murmur if associated bicuspid aortic valve Systolic or continuous murmur radiating to scapula or over thorax from collaterals
Diagnostic testing	CXR • Cardiomegaly • "E" or "reverse 3" sign from dilated left subclavian artery proximal to and poststenotic dilation distal to coarctation • Rib notching from collaterals • Dilated ascending aorta if associated bicuspid aortic valve ECG • Left ventricular hypertrophy TTE • 2D imaging of ascending aorta, aortic arch, isthmus, and descending aorta • Doppler-derived gradient across coarctation • Left ventricular size, systolic and diastolic function, hypertrophy • Other associated congenital heart defects (eg, bicuspid aortic valve, ventricular septal defect, mitral valve anomalies, subaortic stenosis)

Abbreviations: CXR, chest X-ray; ECG, electrocardiogram; TTE, transthoracic echocardiogram.

surveillance examinations, CMR identified clinically significant recoarctation and/or local aneurysm formation in 27% of the cohort.[30] Finally, CMR has been used to identify predictors of coarctation severity as assessed by invasive measurements, which include (1) smallest aortic cross-sectional area measured by gadolinium-enhanced 3D magnetic resonance angiography and (2) heart

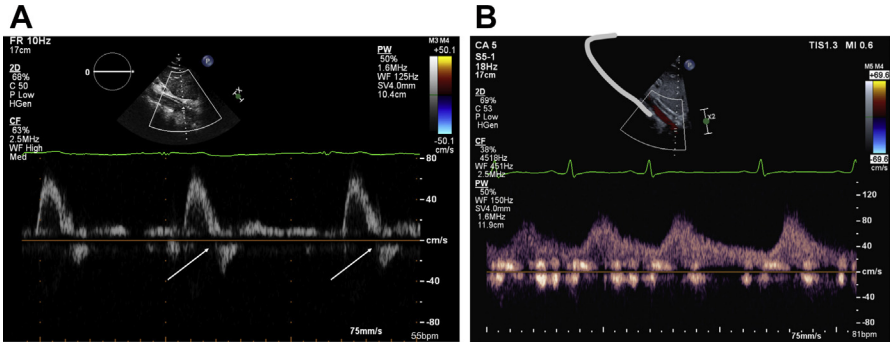

Fig. 2. Normal pulsed-waved Doppler interrogation of the abdominal aorta (*A*) typically demonstrates a brisk upstroke and downstroke followed by early diastolic flow reversal (*arrows*). In contrast, the abdominal Doppler examination in a 21-year-old man (*B*) who underwent previous end-to-end anastomosis demonstrates a dampened, low-velocity signal with continuation throughout diastole suggests significant recoarctation.

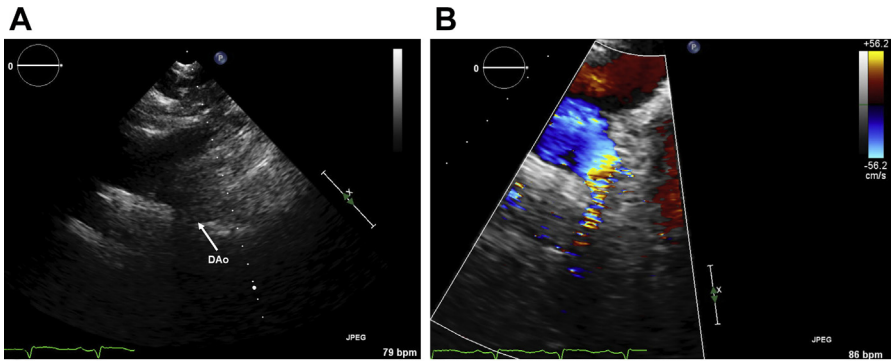

Fig. 3. Suprasternal notch view in an obese 62-year-old man with known bicuspid aortic valve and coarctation of the aorta who underwent previous subclavian flap angioplasty. Images suggest narrowing of the proximal descending aorta (DAo) (*A*). Narrowed appearance supported by color Doppler interrogation (*B*).

rate-corrected mean flow deceleration in the descending aorta measured by phase-velocity cine sequences.[31] CMR provides unrestricted access to the chest and is often regarded as the "gold standard" of imaging in the adult with congenital heart disease. CMR has made valuable contributions to the diagnosis as well as lifelong follow-up evaluation to the adult with CoA.

Cardiac Catheterization

With the advent of advanced 3D imaging techniques, cardiac catheterization is no longer used as a primary diagnostic modality. However, invasive assessment of gradients across the coarctation segment is the gold standard and angiography is essential for assessment of candidacy and planning for transcatheter-based treatment. In older patients with risk factors for coronary artery disease, coronary angiography should be performed as an adjunct diagnostic procedure in preparation for repair.

TREATMENT

Significant coarctation is defined as:

- Resting peak-to-peak gradient greater than 20 mm Hg across the stenosis in the catheterization laboratory or mean Doppler systolic

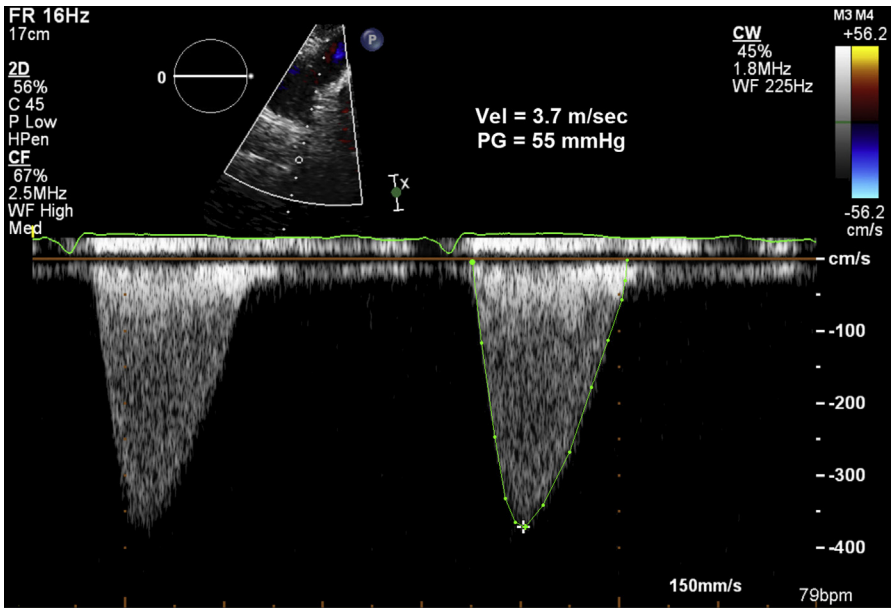

Fig. 4. From the suprasternal view, in the same patient, use of guided Continuous Doppler demonstrates a high-velocity envelope reflective of moderately severe arch obstruction. Advanced imaging is required to further evaluate the arch anatomy.

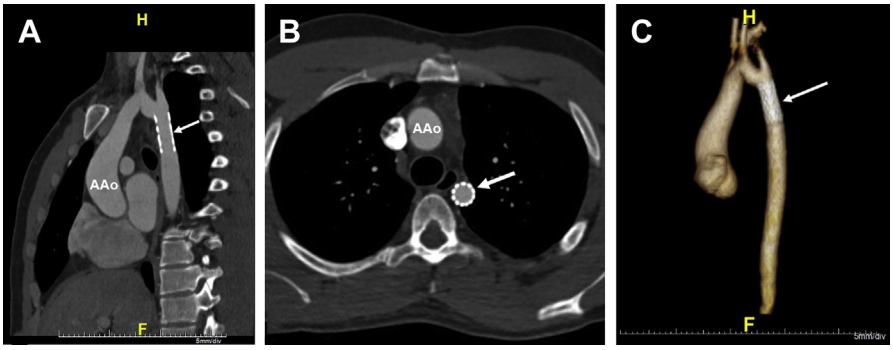

Fig. 5. Computed tomography angiography of the aorta in oblique sagittal (*A*) and axial (*B*) planes demonstrating no evidence of in-stent stenosis (*arrows*) in a 32-year-old patient with coarctation who underwent previous end-to-end anastomosis and later required transcatheter therapy for recoarctation. 3D reconstruction (*C*) displays the luminal contour of the Palmaz stent.

gradient greater than 20 mm Hg by echocardiography OR

- Resting peak-to-peak gradient greater than 10 mm Hg or mean Doppler systolic gradient greater than 10 mm Hg in the presence of decreased left ventricular systolic function, aortic insufficiency, or collateral flow.[32]

However, relatively few data exist to support these cut points historically used to signify risk of sequelae.[33] Several factors need to be considered in selecting the most appropriate method for repair, including age, anatomy of the transverse and descending aorta, history of previous repair, and institutional expertise.

The first surgical repair was performed by Clarence Crafoord in 1944 with resection and end-to-end anastomosis.[34] Since then, many surgical techniques to address coarctation have evolved over time (Fig. 7).[35] The patch aortoplasty involves ligating and dividing ductal tissue, creating a longitudinal incision across the coarctation and prosthetic patch enlargement of the region. Although advantageous in that it can be applied to longer regions of aortic narrowing, avoids a circumferential suture line in the end-to-end anastomosis, and less recoarctation, it is marked by a high rate of aneurysm in the long term—between 18% and 47%[36,37] (Fig. 8). Subclavian flap aortoplasty is a technique in which the left subclavian artery is

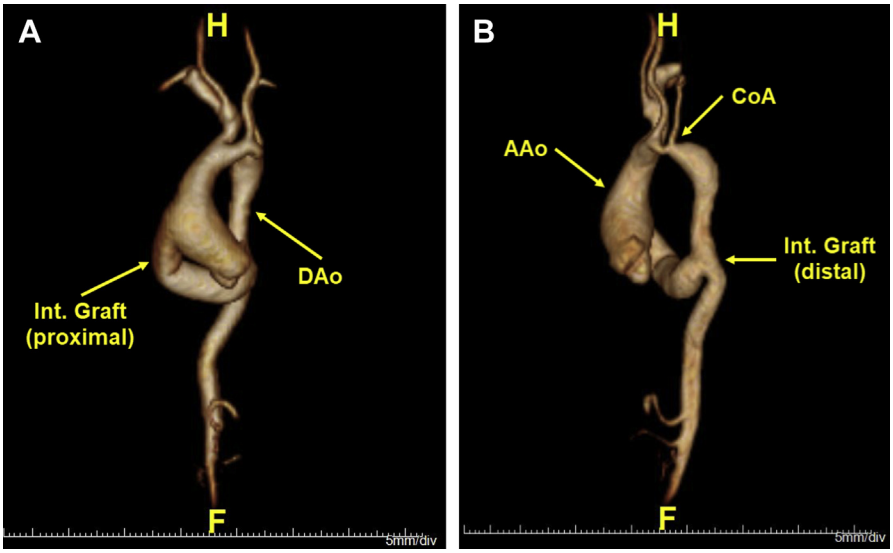

Fig. 6. Volume-rendered 3D reconstructions from a contrast-enhanced MRA examination (*A*, anterior view; *B*, posterior view) in a 57-year-old man with a history of coarctation who underwent surgical repair with an ascending to descending interposition graft (no. 22 mm Hemashield graft). AAo, ascending aorta; CoA, coarctation of the aorta; Dao, descending aorta; Int. Graft, interposition graft.

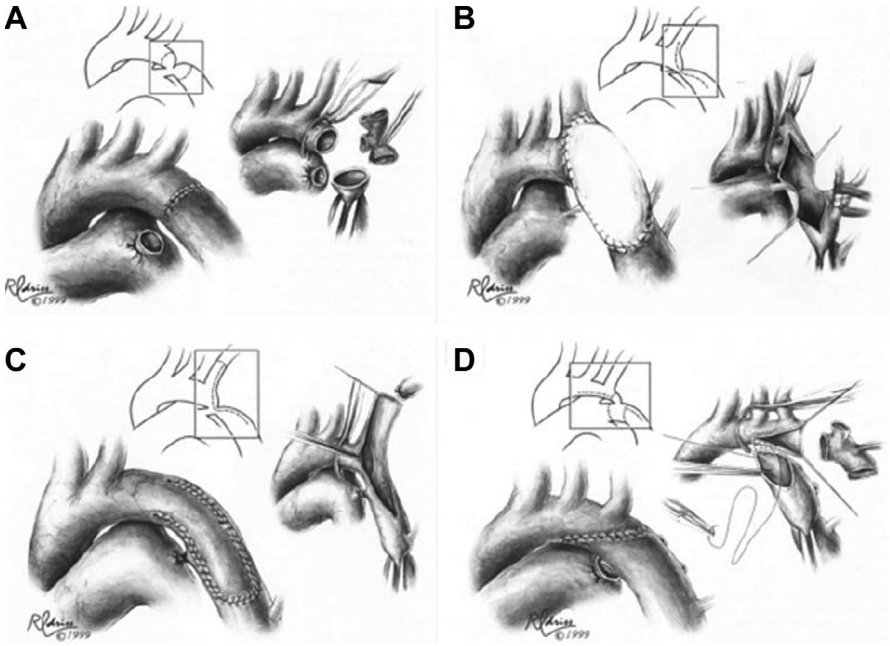

Fig. 7. Surgical techniques of aortic coarctation repair. (*A*) Resection and end-to-end anastomosis. The coarcted segment is resected and a circumferential end-to-end anastomosis is created. (*B*) Patch aortoplasty. Ductal tissue is divided by an incision across the coarctation and patch sutured across the site to enlarge the region. (*C*) Subclavian flap aortoplasty. The left subclavian artery is ligated and divided. A longitudinal incision from the proximal left subclavian artery is made and extended beyond the coarctation. The subclavian flap is turned down and enlarges this area. (*D*) Resection with extended end-to-end anastomosis. The coarcted segment is broadly resected and an oblique anastomosis made between the undersurface of the transverse arch and the proximal descending aorta. (*Adapted from* Dodge-Khatami A, Backer CL, Mavroudis C. Risk factors for recoarctation and results of reoperation: a 40-year review. *J Card Surg.* 2000;15(6):369-377; with permission.)

ligated and divided and turned down onto a longitudinal incision from the proximal left subclavian artery beyond the area of coarctation.[38] Similar to patch aortoplasty in that it avoids circumferential suture lines and can be used for long-segment stenosis, subclavian flap repair can cause retrograde blood flow down the vertebral artery (subclavian steal) and hypoplasia of the left upper extremity with associated claudication. Some patients have been repaired with coarctectomy and interposition graft but this approach is limited by lack of aortic growth in keeping with somatic size when performed in children. The extended end-to-end anastomosis introduced in

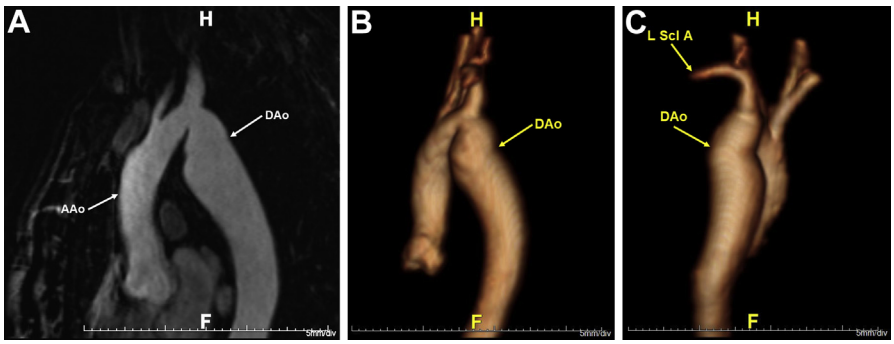

Fig. 8. Contrast-enhanced MRA of the aorta (*A*, oblique sagittal view) and volume-rendered 3D reconstructions (*B*, lateral view; *C*, posterior view) demonstrate an aneurysm in the proximal descending aorta in a 54-year-old man with coarctation of the aorta who underwent patch arterioplasty repair at age 16 years. AAo, ascending aorta; DAo, descending aorta; L Scl A, left subclavian artery.

1977 is a modification of the original technique in which a broad longitudinal incision and anastomosis across the proximal aorta/arch is created.[39]

In 1983, Lock and colleagues[40] described the first use of balloon angioplasty to treat coarctation in infants and children. Although effective in relieving obstruction acutely, balloon angioplasty carries a significant rate of recoarctation in 15%[41] and aneurysm in 24% to 35%.[41,42] Elastic recoil, especially in those of young patients, is believed to be contribute to recoarctation. Intimal and medial tears resulting from balloon angioplasty leading to aortic wall injury may play a role in the long-term development of aortic aneurysm.

Stent implantation became a treatment option in the early 1990s and may be appropriate in adults and adult-size adolescents.[43] Advantages of stent therapy in aortic coarctation include less need for over dilation of the aorta and structural support resulting in lower rates of aortic wall injury and restenosis. In a large observational registry study out of the Congenital Cardiovascular Interventional Study Consortium, outcomes of surgical, stent, balloon and stent angioplasty for native coarctation in 350 patients across 36 institutions were compared. Balloon angioplasty was notable for higher rate of acute and longer-term aortic wall injury.[44]

The Coarctation of the Aorta Stent Trial (COAST) reported short and intermediate outcomes of 105 children and young adults who underwent implantation of a Cheatham-Platinum bare metal stent. At 2 years, 14 patients (13%) required repeat stent dilation but no need for surgical intervention. Twelve of these 14 patients returned for planned reintervention as a result of somatic growth or planned staged therapy. One important outcome was stent fractures that were found in 23, but none were clinically significant. Both acute and late aortic wall injury defined as dissection, aneurysm, or rupture was documented but relatively uncommon.[45]

In general, stent therapy is considered safe and effective in the treatment of native coarctation and is a reasonable option for the adult with simple, discrete native coarctation. Guideline recommendations for therapy and treatment of the adult in aortic coarctation are summarized in **Table 2**.

Table 2
Guideline recommendations for the treatment of the adult with aortic coarctation

AHA/ACC Recommendation	Class/ LOE	ESC Recommendation	Class/ LOE
Surgical repair or catheter-based stenting is recommended for adults with hypertension and significant native or recurrent coarctation of the aorta.	I/B	All patients with a noninvasive pressure difference >20 mm Hg between upper and lower limbs, regardless of symptoms but with upper limb hypertension (>140/90 mm Hg in adults), pathologic blood pressure response during exercise, or significant LVH should have intervention.	I/C
Guideline-directed management and therapy is recommended for treatment of hypertension in patients with coarctation of the aorta.	I/C	Independent of the pressure gradient, hypertensive patients with ≥50% aortic narrowing relative to the aortic diameter at the diaphragm level (on CMR, CT, or invasive angiography) should be considered for intervention.	IIa/C
Balloon angioplasty for adults with native and recurrent coarctation of the aorta may be considered if stent placement is not feasible and surgical intervention is not an option.	IIb/B	Independent of the pressure gradient and presence of hypertension, patients with ≥50% aortic narrowing relative to the aortic diameter at the diaphragm level (on CMR, CT, or invasion angiography) may be considered for intervention.	IIb/C

Abbreviations: AHA/ACC, American Heart Association/American College of Cardiology; CMR, cardiac magnetic resonance; CT, computed tomography; ESC, European Society of Cardiology; LOE, level of evidence; LVH, left ventricular hypertrophy.

Adapted from Stout KK, Daniels CJ, Aboulhosn JA, et al. 2018 AHA/ACC Guideline for the Management of Adults with Congenital Heart Disease: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. J Am Coll Cardiol. 2019;73:1494-1563; and Baumgartner H, Bonhoeffer P, De Groot NM, et al. ESC Guidelines for the management of grown-up congenital heart disease (new version 2010). Eur Heart J. 2010;31:2915–2957.

OUTCOMES

Long-term survival is lower than that of the general population with an overall incidence of mortality of 5%.[46] A large single-center series described long-term outcome of 819 patients (mean age at repair 17.2 ± 13.6 years) who underwent isolated operative repair of coarctation between 1946 and 2005 at the Mayo Clinic. The survival rates were 93%, 86%, and 74% at 10, 20, and 30 years after primary repair, respectively, which were significantly lower than age- and sex-matched controls.[47] The most common cause of late death was coronary artery disease, followed by sudden death, heart failure, cerebrovascular accident, and ruptured aortic aneurysm. Coronary artery disease does not seem to be independently predicted by coarctation alone and likely mediated by other coexistent risk factors.[48,49] However, when patients with coarctation do experience myocardial infarction, it occurs at a significantly younger age than in those without coarctation.[50] Therefore, it is imperative that those who have undergone repair are monitored longitudinally for the development of complications and that risk factors for atherosclerosis are aggressively treated and managed.

Systemic Hypertension

Surgical and transcatheter repair of aortic coarctation decreases hypertension and use of antihypertensive medication.[44,51–53] However, systemic hypertension is one of the major long-term morbidities after repair of aortic coarctation. Persistent or recurrent hypertension and exercise-induced hypertension can develop after repair, especially in patients whose repairs are performed later in life, older age at follow-up, and those with residual narrowing.[47] A risk factor for exercise-induced hypertension is hypoplastic aortic arch or mild coarctation, even in the absence of a significant gradient.[54] When combining resting blood pressure, ambulatory blood pressure monitoring, and exercise testing, systemic hypertension has been reported in as many as 70% of patients after coarctation repair.[55]

Abnormalities of vascular function, including decreased compliance of the aortic wall, endothelial dysfunction, and dysregulation of the renin-angiotensin system are factors that contribute to hypertension.[56] Regardless of type of repair, vascular stiffness and decreased compliance remain.[19,57] In a small, randomized crossover study in 20 normotensive patients with repaired aortic coarctation, Ramipril improved maximum hyperemic forearm blood flow and decreased circulating levels of proinflammatory cytokines (interleukin-6) and molecules (sVCAM-1 and sCD40 L), suggesting that targeting the renin-angiotensin pathway could be used as a treatment for vascular dysfunction in repaired coarctation.[58] However, there are no guidelines regarding specific antihypertensive agent for the treatment of hypertension in coarctation (see **Table 2**).

When hypertension is detected at rest, recoarctation must be excluded by physical examination (brachial/femoral pulse delay, arm/leg blood pressure gradient), Doppler echocardiography, and/or CMR or cardiac CTA. Recoarctation should be evaluated and candidacy for transcatheter therapy (ie, stent angioplasty) should be determined. If there is no evidence of recoarctation, medical management for hypertension is indicated. Assessment of activity-related hypertension is performed with a 24-hour ambulatory blood pressure monitor or exercise study to determine peak systolic blood pressure at maximal exercise and should be a component of long-term care (**Table 3**).

Recoarctation

Recurrent coarctation refers to restenosis after an initially successful intervention. Symptoms suggestive of recoarctation are headaches or claudication, although many patients are asymptomatic and present with hypertension. The rate of recoarctation is up to 34% after surgery[37] and is seen primarily in children, usually due to inadequate aortic wall growth at the site of repair when surgery is performed before the aorta has reached adult size. In addition to end-to-end repair, restenosis can also be seen in patients who have undergone subclavian flap arterioplasty as residual ductal tissue is left behind and interposition graft for long-segment stenosis. Following balloon angioplasty, children are also at greater risk for recoarctation compared with adults, with rates up to 50% in infants and neonates compared with 9% in young adults likely due to higher elastic recoil in younger patients.[59,60]

Indications for intervention for recoarctation are similar to those for native coarctation and include hypertension, a peak instantaneous pressure gradient across the coarctation of ≥20 mm Hg, and/or imaging evidence of collateral circulation.[32,61] Discrete coarctation in older children and adults is treated with percutaneous balloon angioplasty, often with stent therapy, although surgical repair may be necessary for complex cases, including long-segment recoarctation, hypoplastic aortic arch, and associated aneurysm or pseudoaneurysm.

Table 3
Guidelines for routine follow-up and testing intervals in aortic coarctation

Frequency of Routine Follow-Up and Testing	Physiologic Stage A[a] (mo)	Physiologic Stage B[a] (mo)	Physiologic Stage C[a] (mo)	Physiologic Stage D[a] (mo)
Outpatient ACHD cardiologist	24	24	6–12	3–6
ECG	24	24	12	12
TTE[b]	24	24	12	12
CMR[c]/Cardiac CT[d]	36–60	36–60	12–24	12–24
Exercise test[e]	36	24	24	12

Abbreviations: ACHD, adult congenital heart disease; CMR, cardiovascular magnetic resonance imaging; CoA, coarctation of the aorta; CPET, cardiopulmonary exercise; CT, computed tomography; ECG, electrocardiogram; NYHA, New York Heart Association; TTE, transthoracic echocardiogram.

[a] Physiologic Stage A: NYHA FC I, no hemodynamic or anatomic sequelae, normal exercise capacity. Physiologic Stage B: NYHA FC II, mild hemodynamic sequelae (mild aortic enlargement, ventricular dysfunction, or valve disease), abnormal exercise function testing. Physiologic Stage C: NYHA FC III, at least moderate aortic enlargement, ventricular dysfunction, or valve disease, end-organ dysfunction responsive to therapy. Physiologic Stage D: NYHA FC IV, severe aortic enlargement, refractory end-organ dysfunction.

[b] Routine TTE may be unnecessary in a year when CMR imaging is performed unless clinical indications warrant otherwise.

[c] CMR may be indicated for assessment of aortic size and aortic arch/coarctation repair site anatomy. Baseline study is recommended with periodic follow-up CMR, with frequency of repeat imaging determined by anatomic and physiologic findings.

[d] CT may be used if CMR is not feasible and to evaluate cross-sectional imaging status–post-stent therapy for coarctation of the aorta; the frequency should be weighed against radiation exposure.

[e] Six-minute walk test or CPET, depending on the clinical indication.

Adapted from Stout KK, Daniels CJ, Aboulhosn JA, et al. 2018 AHA/ACC Guideline for the Management of Adults With Congenital Heart Disease: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. J Am Coll Cardiol. 2019;73:1494-1563.

Aortic Aneurysm/Pseudoaneurysm and Dissection

Diagnosis and surveillance for late aortic complications after coarctation repair, either surgical or percutaneous, requires intermittent 3D assessment of the coarctation site, including CMR or CTA to assess for aneurysm, pseudoaneurysm, recoarctation, stent fracture, and/or migration.

An aortic aneurysm may develop at the site of previous coarctation years after surgery (especially after patch angioplasty), balloon dilation, or stent implantation of native coarctation and can occur despite relief of systemic hypertension or residual/recurrent coarctation. The rate of aneurysm formation ranges between 3% and 20%.[47,62,63] Risk factors for postrepair aneurysms are older age at the time of coarctation repair, patch angioplasty technique, and bicuspid aortic valve.[64,65]

Pseudoaneurysms at the coarctation repair site demonstrate an area of weakening with outpouching of the adventitial thin layer of the aorta, usually along the suture line. At increased risk for rupture, pseudoaneurysms should be considered for repair at the time of diagnosis. Vascular dysfunction may be the underlying mechanism contributing to the development of aneurysm or pseudoaneurysm associated with repaired coarctation of the aorta.

For most patients, aneurysm or pseudoaneurysm repair requires surgical intervention with resection of the aneurysm and graft placement. Alternatively, endovascular stent grafts have been used with more frequency. The COAST II trial published results on the Cheatham-Platinum stent covered with an expandable sleeve of ePTFE in 158 children and adults with aortic coarctation and either evidence of aortic wall injury or risk factors for such. The theoretic benefits of a covered stent to prevent aortic wall injury have been documented.[66] The COAST II trial has shown efficacy in the use of covered endovascular stents for aortic wall injury, including aneurysm and pseudoaneurym.[45]

Reintervention

Of the 819 patients operated on at the Mayo Clinic described above, there were 175 reinterventions in 124 patients. Freedom from reintervention of the descending aorta were 97%, 92%, and 89% at 10, 20, and 30 years with older age and end-to-end anastomosis technique independently associated with lower rate of reintervention. In fact, the

highest rate of reintervention was in patients less than 5 years at the time of repair. The most common reason for any cardiac reintervention (not just the descending aorta), however, was aortic valve surgery.[47]

Left Ventricular Dysfunction

With increased aortic stiffness, there is evidence to support impaired ventriculo-arterial coupling, which impacts left ventricular performance. Despite successful repair and normotension, patients with aortic coarctation have been shown to have increased left ventricular mass[67] and diastolic dysfunction.[68] Global longitudinal and radial strain are decreased late after coarctation repair in the face of normal left ventricular ejection fraction, suggestive of subtle impairment of left ventricular function.[69,70] Left ventricular contractile reserve in response to exercise is also abnormal and related to exaggerated blood pressure response to exercise.[71] Left ventricular fibrosis has been demonstrated in an animal model of repaired coarctation,[72] which may also play a role in the development of ventricular dysfunction and predisposition toward heart failure in this population.

Cerebral Aneurysm and Stroke

Intracranial aneurysm is found in approximately 10% of patients with aortic coarctation as diagnosed by CTA and magnetic resonance imaging with older age as a risk factor.[73,74] It occurs with a frequency of 5-fold compared with the general population.[75]

High rates of cerebrovascular accidents are a historical morbidity associated with unrepaired coarctation and hypertension. The prevalence of stroke in patients with aortic coarctation is not well described but these patients experience both hemorrhagic and ischemic stroke at significantly younger age compared with the general population.[76] Hemorrhagic stroke is related to intracranial aneurysm but the relationship between these aneurysms, coarctation, and stroke are not entirely clear.

The association of intracranial aneurysm and coarctation is thought to be related to either developmental abnormalities of the arterial wall or pathologic changes as a result of mechanical forces attributable to hypertension.[77] Just as aortic endothelial dysfunction has been demonstrated, there is evidence that the cerebral vasculature of those with aortic coarctation have increased stiffness and less vasoreactivity.[78] Furthermore, reduced aortic distensibility has been shown to result in greater transmission of aortic forward wave energy into the carotid artery on vascular studies of young adults with repaired coarctation, which may contribute to cerebrovascular disease.[18]

Vascular abnormalities, including vertebral artery hypoplasia and incomplete posterior circle of Willis, are associated with increased cerebral vascular resistance. There is a significantly higher prevalence of both of these cerebral vascular abnormalities in aortic coarctation patients compared with the general population and is an independent risk factor for hypertension, highlighting another potential mechanism linking stroke and hypertension in aortic coarctation.[79]

Many of these intracranial aneurysms are small and do not require treatment but there is no consensus on screening and surveillance of such aneurysms when found. The current American Heart Association/American College of Cardiology Guidelines on the management of adults with congenital heart disease state that it may be reasonable to screen for intracranial aneurysm giving it a class IIb recommendation with level of evidence B.[32] In the authors' institutions, consideration is given to patient age, risk factors, presence of new headache, and/or plans for systemic anticoagulation in the setting of cardiopulmonary bypass.

PREGNANCY

Because medical, surgical, and catheter-based therapies have advanced, the number of women living into adulthood and reaching childbearing years has grown. Preconception counseling is crucial to provide the most well-informed risk assessment for the individual patient. This includes up-to-date cardiac imaging, ECG, cardiopulmonary exercise test to evaluate functional capacity, review of medications that may pose a risk to a fetus, and discussion of potential for familial/genetic influence on a fetus. All women with congenital heart disease should undergo a fetal echocardiogram to screen for congenital heart disease in the fetus at ~20 weeks' gestation.

Women with aortic coarctation, repaired or unrepaired, are at risk for untoward cardiovascular outcomes and specifically are at increased risk for hypertensive disorders of pregnancy.[80] The frequency of a hypertensive complication was 24.1% ± 3.3% for women with coarctation compared with 8.0% ± 0.1% for women without coarctation in a study examining pregnancy outcomes in a nationally representative sample.[81] Aortic dimensions appear to correlate with adverse cardiovascular outcome in pregnancy. In a study of women who underwent CMR examinations before pregnancy, women with an aortic diameter of 12 mm (7 mm/m^2) or less were more

likely to experience hypertensive complications.[82]

For these reasons, women with repaired coarctation are classified as World Health Organization (WHO) category II–III, which is defined as moderate increase for maternal morbidity and mortality.[83] In this case, pregnancy is not contraindicated but monitoring should take place throughout the pregnancy by both the adult congenital heart disease provider as well as with high-risk obstetrics/maternal fetal medicine. Patients with severe, native coarctation are considered WHO category IV or high risk for maternal morbidity and mortality and pregnancy is contraindicated.[83] If unplanned pregnancy occurs discussion regarding termination should take place.

There are numerous hemodynamic changes that occur throughout pregnancy in the woman with congenital heart disease. These hemodynamic changes can abruptly change during delivery and the postpartum period. During the second stage of labor, pushing is essentially a Valsalva maneuver that can impair venous return thereby decreasing cardiac output. In those with coarctation (native or recurrent), this drop in cardiac output can be severe and life-threatening. Therefore, a detailed delivery plan that includes an assisted second stage (use of forceps or vacuum) to minimize time spent pushing is recommended. An arterial line may also be placed to monitor blood pressure continuously. Ultimately, care should be individualized within the context of a multidisciplinary team. Women with repaired coarctation can undergo a successful pregnancy and delivery with appropriate preconception evaluation and careful monitoring.[83]

SUMMARY

Although often a simple discrete lesion, there can be a wide spectrum of aortic arch anatomy in aortic coarctation. The evolution in treatment of aortic coarctation over the past 3 decades has demonstrated improvements in survival for this condition but, despite successful repair, adults with aortic coarctation continue to experience excess morbidity and premature mortality associated with hypertension, heart failure, cerebrovascular accident, coronary artery disease, and aortic dissection/rupture. The understanding of aortic coarctation as a diffuse aortopathy may explain some of these long-term morbidities. This ongoing hazard warrants lifelong surveillance and follow-up with specialists in congenital heart disease to screen for and monitor late-onset complications.

DISCLOSURE

The authors have nothing to disclose.

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