Chapter 13
Stenting in Aortopathies

Joanna Ghobrial and Jamil Aboulhosn

Abstract Transcatheter stent deployment within the aorta is generally used for two purposes: (1) relief of aortic obstruction as seen in aortic coarctation and (2) the use of covered stents to exclude an aneurysm or pseudoaneurysm of the aorta. For the purpose of relieving obstruction, balloon angioplasty alone is associated with reasonable short-term improvement in stenosis severity but limited by a high incidence of restenosis and aneurysm formation. Uncovered large diameter stent platforms are a more durable alternative for relief of stenosis but do not obviate the risk of aneurysm formation and do not protect the aorta in cases of rupture, dissection, or pseudoaneurysm formation. Covered balloon expandable stent platforms are ideal for relief of stenosis and reduce the risk of extravascular hemorrhage, dissection, and aneurysm formation. Transcatheter stent placement has become the treatment modality of choice for most children and adults with native coarctation or those with postsurgical sequelae or complications. The advent of large diameter self-expanding covered stent grafts allows for treatment of complex aneurysms, pseudoaneurysms, and dissections. Hybrid transcatheter and surgical techniques can also be utilized to treat hypoplasia and focal coarctations of the aortic arch. This chapter will review the role of transcatheter stenting for the treatment of aortopathies that are manifested by obstruction, aneurysm formation, or both.

Keywords Aortopathy • Coarctation • Stent • Angioplasty • Aneurysm

13.1 Aortopathy and Coarctation and Indications for Intervention

Aortopathy is defined as any disease of the aorta. This includes the inherited connective tissue disease syndromes with related aortic disease such as Marfan, Ehlers-Danlos, Loeys-Dietz, bicuspid aortic valve-associated aortopathy, and the

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aortopathy associated with aortic coarctation. This section specifically considers aortopathies that can be intervened upon in the cardiac catheterization laboratory using stenting techniques, specifically native and postsurgical aortic coarctation, with or without aneurysm.

On histology, the aortic wall consists of three layers: the intima (the innermost layer with endothelial lining), the media (the muscular layer and contains smooth muscle cells, fibrillin, elastin, and collagen), and the adventitia (the outer lining) [1–3].

Aortopathies are related to abnormalities in the connective tissue of the aorta. On histologic examination, there is degeneration and disruption of smooth muscle cells, collagen, elastin, and fibrillin in the aortic media [3].

A coarctation of the aorta consists of a narrowing of a segment of the aortic arch that leads to varying degrees of obstruction, which causes hypertension proximal to the narrowing and lower pressure beyond. The most frequent location of a simple coarctation is just distal to the takeoff of the left subclavian artery at the area of the ductus/ligamentum arteriosum. Less common is a coarctation in the abdominal aorta or a diffusely narrowed aortic arch. Collateral vessels may arise proximal to the obstruction to help supply the distal organs, notably these collaterals can also mask the degree of obstruction on clinical examination or Doppler interrogation by allowing the distal aortic pressure to be adequately maintained. There are two possible underlying concepts explaining the development of coarctation. The first concept is related to blood flow limitation during development with outflow obstruction lesions such as aortic stenosis leading to the coarctation, the second is related to abnormal ductal tissue extending into the arch leading to constriction with ductal closure, supporting the latter concept is presence of abnormal smooth muscle and collagen in the aortic tissue surrounding the coarctation, and this also explains the predilection of the surrounding tissue to dissection and rupture [4–8].

Coarctation of the aorta is a common congenital heart lesion affecting 6–8 % of patients with congenital heart disease; it occurs up to two times more commonly in males than in females. While coarctation can present as the sole lesion, it can also present in association with other congenital conditions such as bicuspid aortic valve, ventricular septal defect, patent ductus arteriosus, aortic stenosis, subaortic stenosis, supravalvular aortic stenosis, and mitral valve abnormalities, as well as circle of Willis cerebral artery aneurysm and genetic conditions such as Turner syndrome [9–15].

Surgical repair of aortic coarctation was first described in 1944 by Crafoord et al. [16], and balloon dilation was first mentioned in 1979 [17], introduced in 1982 by Singer et al. [18], and performed in 1991 [19]. Medical therapy with beta-blockers, ACE-inhibitors, or angiotensin-receptor blockers is typically employed to control hypertension and to decrease shear stress in the abnormal aortic tissue. In adults, accepted indications for intervention to relieve native aortic coarctation include [20] (Fig. 13.1):

- Peak-to-peak coarctation gradient greater than or equal to 20 mmHg

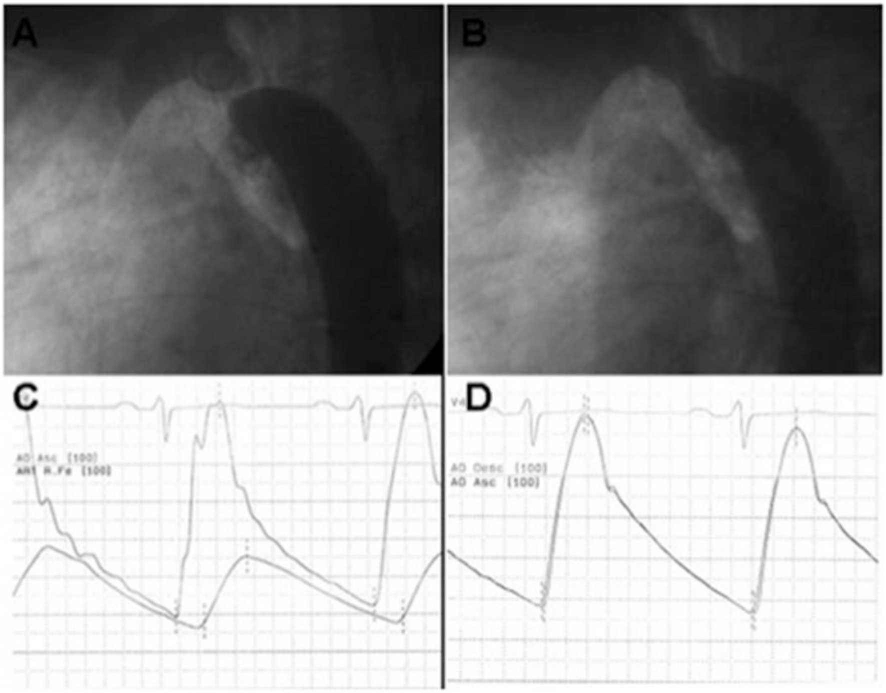

Fig. 13.1 (**a**) Aortic angiogram, lateral projection demonstrating near interruption of the distal aortic arch. (**b**) Angiogram following stent placement demonstrating a patent aorta without evidence of dissection or pseudoaneurysm. (**c**) Simultaneous ascending and descending aortic pressures. The ascending aortic systolic pressure is 80 mmHg higher than the descending aortic pressure distal to the coarctation. Also note that the ascending aortic diastolic pressure is also greater, and there is a delayed upstroke of the descending aortic systolic pressure; these findings are consistent with a severe fixed obstruction of the aorta. (**d**) Simultaneous pressure ascending and descending aortic pressures following successful stent deployment demonstrating no residual systolic or diastolic gradient and rapid systolic upstroke of both waveforms

- Imaging evidence of significant coarctation, with a peak-to-peak coarctation gradient less than 20 mmHg due to collateral flow (collaterals will decrease the gradient despite a hemodynamically significant coarctation)

Furthermore, for recoarctations, percutaneous stent placement is favored for discrete narrowing, whereas surgical intervention may be preferable for long-segment hypoplasia and aortic arch hypoplasia.

The European Society of Cardiology (ESC) [21] guidelines for the treatment of adult congenital heart disease list the following indications for intervention:

- Gradient >20 mmHg between upper and lower limbs.
- Upper limb hypertension.
- Pathological BP response to exercise.

- Aortic coarctation diameter <50 % of the diameter of the aorta at the level of the diaphragm.

In many ACHD centers presently, surgery is reserved for cases that are not amenable to percutaneous intervention, whether native coarctation or recoarctation, such as long tortuous segments, large aneurysms, and transverse aortic arch hypoplasia. There has been some experience in small series of patients with successful percutaneous stenting of transverse arch hypoplasia. Partial or complete coverage of the arch vessels with uncovered stents does not appear to cause significant obstruction to flow through these vessels but is nevertheless generally avoided due to concerns over thromboembolism [22–24]. The use of self-expanding covered stent grafts or covered stents within the aortic arch is accompanied by surgical bypass of occluded vessels (Fig. 13.2). In some cases where surgical aortic valve or ascending aortic repair or replacement is necessary in a patient with a coexistent coarctation of the aorta, transcatheter stenting of the coarctation can be performed at the time of or before surgical intervention. The complications of surgical repair in adults with coarctation, or recoarctation, are not negligible. Such complications include extensive bleeding from collaterals, severe rebound hypertension early after repair, recurrent laryngeal or phrenic nerve palsy, need for cardiopulmonary bypass, aneurysm or pseudoaneurysm formation especially with Dacron patch

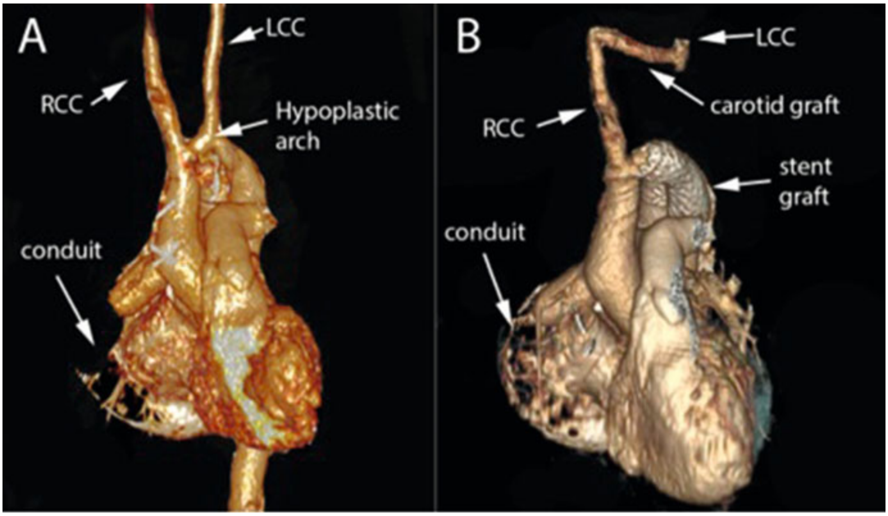

Fig. 13.2 (**a**) CT angiogram with 3-D volume rendering, shallow left anterior oblique view, demonstrating a hypoplastic aortic arch in a patient that had previously undergone surgical placement of an ascending to descending aortic conduit. The conduit had subsequently thrombosed. The right common carotid (RCC) and left common carotid (LCC) are labeled. The left subclavian artery is not visualized because it had previously been utilized to surgically augment the aorta as a subclavian flap. (**b**) Covered aortic stent graft placement within the aortic arch has increased the arch diameter. A surgically placed carotid bypass graft ensures flow from the patent RCC to the LCC

repair, subclavian steal syndrome, and rarely paraplegia due to spinal cord ischemia [25]. Complications of coarctation stenting include major aortic complications such as rupture, dissection or pseudoaneurysm formation in ~ 1 % of patients, [26] femoral arterial injury, bleeding, stent fracture, or stent embolization (Figs. 13.3 and 13.4).

Unlike stenting in aortic coarctation, which is oftentimes used as line treatment, stenting in other aortopathies due to underlying connective tissue disease, such as

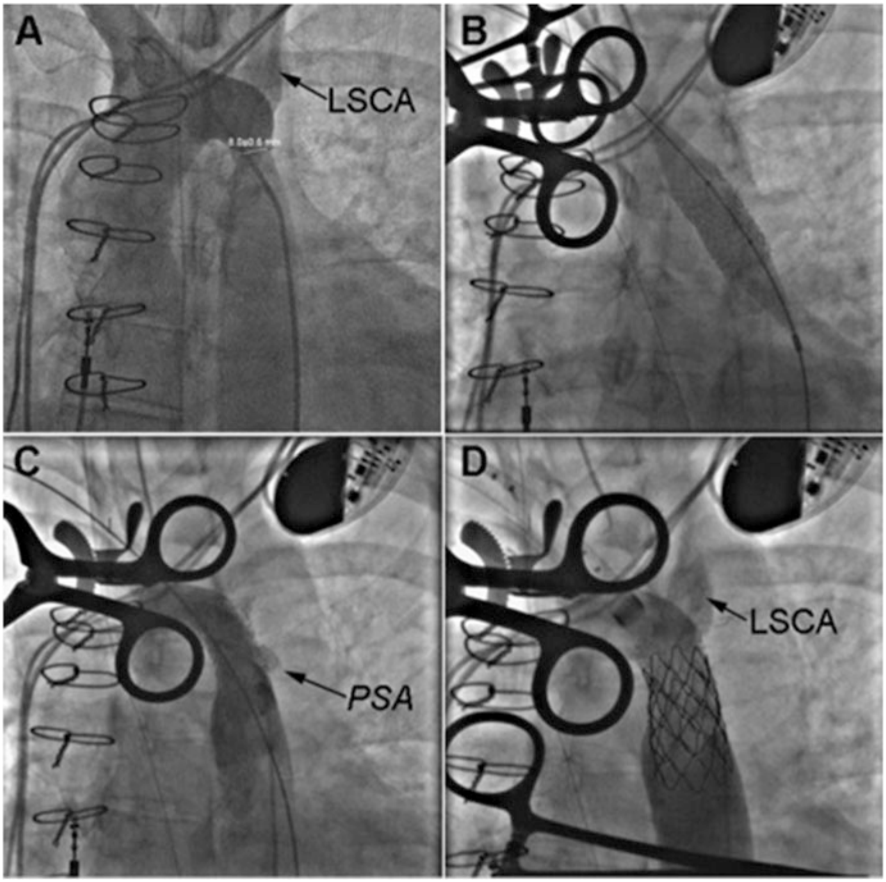

Fig. 13.3 (**a**) Aortic angiogram demonstrating a residual coarctation distal to the left subclavian artery in a patient that had undergone surgical end-to-end repair as a child yet developed upper extremity hypertension in adulthood. (**b**) High pressure balloon expansion of an uncovered stent with minimal residual waist. (**c**) Rotational angiography demonstrated an expanding pseudoaneurysm (PSA) at the site of stent deployment. (**d**) Angiogram following deployment of a covered stent with occlusion of the PSA. Note the left subclavian artery is not obstructed by the covered stent. Also note that arterial access for this case was via surgical cutdown of the right subclavian artery due to obstruction of both femoral arteries from prior catheterization procedures during childhood

Fig. 13.4 Rotational aortic angiogram with 3-D volume rendering demonstrating an uncovered stent that embolized from its initial position just distal to the left subclavian artery to the mid-descending thoracic aorta. The *yellow arrow* points to an aneurysm or pseudoaneurysm

Marfan syndrome, is reserved for high-risk surgical patients. While endovascular repair of aneurysms and dissection due to underlying connective tissue disease has been shown to be feasible [27–30], it has also been associated with higher risk of dissection extension, endoleaks, stent graft migration, high re-intervention rates, and need for conversion to open surgical repair [31–34], and that is why expert consensus documents have recommended reserving stenting in patients with connective tissue disease-related aortopathies to only those with prohibitive surgical risk [35, 36].

13.2 Procedure Mechanism and Technique

Percutaneous intervention in aortic coarctation initially consisted of balloon dilation, but this technique has been supplanted by stent placement due to the decreased efficacy and increased risk of dissection or aneurysm formation with balloon angioplasty alone. Balloon dilation of narrowed segments in vessels involves the creation of small intimal and medial tears that heal with time. In fact, intravascular ultrasound study by Sohn et al. [37] confirmed the occurrence of such tears post angioplasty, with follow-up ultrasounds showing resolution and evidence of remodeling. However this very mechanism also can lead to aneurysm formation with a rate ranging from 2 % to as high as 20 % post-balloon angioplasty, especially in the setting of underlying aortopathy [19, 38–42].The advent of stenting of the coarctation has decreased this high rate of aneurysm formation and has now become the treatment of choice in older children and adult patients. The stent buttresses the aortic wall including the areas with intimal flaps or dissections [19, 43, 44], and this is also one of the main reasons why overdilation and oversizing are avoided.

Pre-procedural planning is essential, and the use of multiple imaging modalities aids in achieving a successful result. Echocardiography will evaluate for the presence of associated congenital lesions, such as left-sided outflow lesions or valvular abnormalities. Echocardiography also measures Doppler gradients across the coarctation, but such gradients are unreliable in the presence of collaterals. The echocardiogram can be limited however in assessing the size and dimensions of the coarctation, especially in relation to the aorta at the level of the diaphragm; that is where MRI or CT imaging is invaluable as it provides anatomic, and in the case of MRI also functional, evaluation of the aortic arch [45–47].

The procedure is typically performed under general anesthesia or deep sedation in adults; cross-matched blood should be available in the cardiac catheterization lab. The femoral artery is the preferred approach. Heparin is used as the procedural anticoagulant using 70–150 IU/Kg intravenously, with an activated clotting time (ACT) maintained >200 s. A femoral arterial sheath is inserted, an end-hole catheter is advanced over a soft-tip J wire in a retrograde fashion into the ascending aorta, and a pullback gradient is obtained. Alternatively, a separate radial artery line can be placed for continuous upper extremity pressure measurement. In cases where femoral arterial anatomy is prohibitive, a hybrid approach can be utilized with surgical cutdown and arterial access via the subclavian artery (Fig. 13.3).

After the hemodynamic assessment, the anatomy of the transverse arch and the coarctation is obtained with angiographic projections in the lateral and either left/right anterior oblique (20°) or anteroposterior views depending on right- or left-sided arch anatomy. Rotational angiography may be utilized if available and provides excellent three-dimensional assessment of the aorta (Figs. 13.4 and 13.5). Measurements made include the narrowest portion of the coarctation, the transverse arch, the ascending aorta, and the aorta distal to the coarctation and at the level of the diaphragm. The length of the narrowing is also measured to aid in stent sizing. The origins of the brachiocephalic, carotid, and subclavian arteries are noted, and presence of aneurysms is assessed.

The interventional portion of the procedure starts by introducing a stiff guidewire through the catheter into the ascending aorta or subclavian artery. If the coarctation is not more than 10 mm from the origin of the left subclavian artery, then positioning the wire there should be avoided as stent migration can cause "jailing" of this artery. The tip of the guidewire must be maintained at all times away from the coronary ostia, the carotid, and vertebral arteries.

Balloon angioplasty to "prepare" the lesion for stenting was previously widely utilized but has been generally abandoned due to concerns for aortic dissection, rupture, or aneurysm formation. If angioplasty is considered, it is imperative that the balloon size does not exceed that of the dimensions of the aorta at the level of the diaphragm and does not exceed two times the size of the minimal coarctation dimension [48–50]. The shortest balloons covering the length of the coarctation are

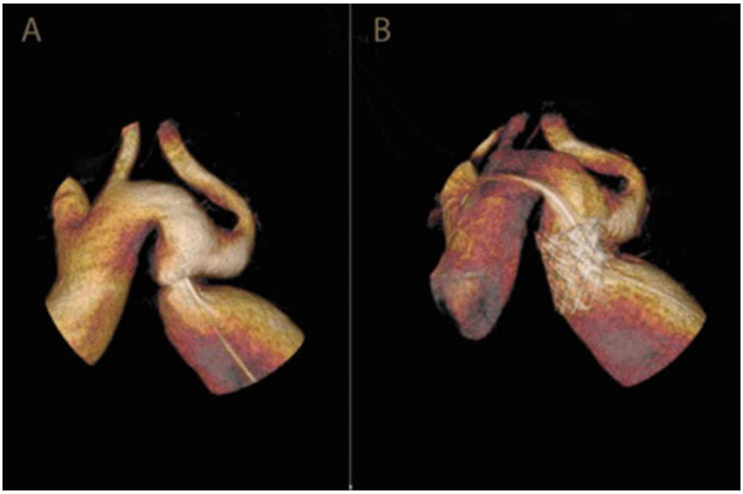

Fig. 13.5 (**a**) Rotational angiography with 3-D volume rendering demonstrating focal coarctation distal to an ectatic left subclavian artery. (**b**) Uncovered stent placement with resolution of the stenosis and minimal overlap with the ostium of the left subclavian artery

preferable. The balloon should be centered at the coarctation and should be inflated until the waist disappears or until maximum inflation pressure is achieved which is usually around 6 atm. The inflation time is approximately 10–15 s. The balloon should be kept away from the carotid and vertebral arteries. Once the balloon is rapidly deflated and removed, a catheter is then used to assess gradient across the coarctation and repeat angiography to ensure no dissection, aneurysm, or perforation/rupture has occurred.

Stent selection is based on the severity, length, and location of the narrowing. Large diameter uncovered hepatobiliary stents (Palmaz XL, Palmaz Genesis, ITI Mega and Max LD) are widely utilized and come in a variety of lengths and potential diameters (Fig. 13.5). Attempts should be made to avoid "jailing" the subclavian artery or the carotid artery, but there is little data to suggest that doing so is associated with significant obstruction to flow in these vessels. The diameter of the aorta at the diaphragm is typically used as the goal diameter to which the stent should be expanded; however, in order to minimize the risk of rupture or dissection, care should be taken to avoid increasing the coarctation diameter by more than 2.5-fold when using uncovered stents. A long large diameter sheath (10–14 Fr) is favored for stent deployment. A number of large diameter balloons are commercially available for stent deployment; however, the favored balloon is the NuMED balloon in balloon (BIB), which allows for expansion of a smaller inner balloon followed by a larger outer balloon. This technique allows for more precise stent positioning during deployment and minimizes the risk of stent deformation during expansion. Rapid ventricular pacing (at 160–200 bpm) may be used to produce transient decrease in systolic blood pressure (to <50 mmHg) to avoid stent movement or migration during inflation. Further dilation with larger balloons may be performed to achieve a satisfactory hemodynamic and anatomic result. The stent is often expanded 70–80 % of the diameter of the aorta at the level of the diaphragm to reduce the potential for complications including dissection and rupture. After balloon withdrawal, gradient measurements and repeat angiography should be performed to assess hemodynamic success and rule out any major vascular complications.

Despite the lack of proven efficacy in this setting, but based on known efficacy in coronary stenting, aspirin is often used for a minimum of 6 months post-stent placement. We recommend continuing long-term aspirin if a portion of the stent covers the arch vessels or if the stent is not well apposed to the proximal or distal aortic wall. Antibiotics are administered at the time of stent placement. Repeat imaging is indicated at approximately 3–6 weeks post procedure to exclude dissection, aneurysm formation, recoarctation, stent migration, or thrombosis and should be performed at regular intervals with echocardiography and Doppler [51]. We recommend performing a follow-up chest CT angiogram or MRI within 1–2 years of stent placement or sooner if there are concerning clinical examination, echocardiographic, or chest X-ray findings.

13.3 Outcomes of Intervention for Aortic Coarctation and Stent Choice

Outcomes of balloon angioplasty compared to surgery are available mostly in the pediatric population, where both intervention methods provided similar acute gradient reduction and decrease in systolic blood pressure, with lower procedure-related complications and shorter hospital stay in the angioplasty group but with higher recoarctation and aneurysm formation [42, 52, 53]. Factors predicting worse acute results included transverse arch hypoplasia, higher initial gradient, and older age [48–50, 53–63].

Long-term outcomes post-balloon angioplasty also highlight the increased risk of aneurysm formation and need for re-intervention post angioplasty compared to surgery. It is important to note however that surgical approach for patient with recoarctation is associated with an increased mortality as high as 7 % relative to native coarctation [41, 48–50, 55, 64–74].

The pathophysiology behind the higher rate of recoarctation and aneurysm formation post angioplasty is thought to be secondary to the stretch caused by the inflating balloon leading to wall damage and disruption of the aortic wall elastic properties. The intimal and medial tears are the recognized mechanism of angioplasty [75, 48]. However, the degree of stretch and aortic wall disruption, as well as the degree of underlying medial abnormality, thinning, and calcification, will increase the risk of adverse outcomes post angioplasty [4, 6, 76].

In order to address the significant rates of recoarctation and aneurysm formation with balloon angioplasty [66, 53], stenting has now become the mainstay of percutaneous intervention in aortic coarctation, with the exception of young infants and children where surgery and balloon angioplasty are still the preferred methods. Outcomes post stenting prove that it is a safe and effective approach to aortic coarctation and recoarctation with a significant reduction in gradient and systolic blood pressure, as well as a decreased risk of restenosis, dissection, and aneurysm formation. It is important to note, however, that in the adult population, the initial gradient may not reflect the severity of the obstruction due to the presence of collaterals; hence, the degree of gradient reduction post stenting is not a reliable measure of success. Also, studies have shown that some adult patients without residual stenosis will continue to be hypertensive, and that is thought to be due to underlying vascular disease and aortopathy [77–82].

There are three main types of stents:

1. Uncovered balloon expandable metallic stents
2. Covered balloon expandable stents (with a layer of PTFE)
3. Self-expanding covered stent grafts

Uncovered balloon expandable stents were developed for hepatobiliary interventions but are widely used for coarctation interventions. They are associated with improved procedural safety and efficacy when compared to balloon angioplasty alone; however, the incidence of aneurysm formation is persistent, and there is a low risk of stent fracture [83, 84]. Covered balloon expandable stents are now preferentially used in the treatment of aortic coarctation in much of the world but as of the time of the writing of this chapter are still not commercially available or approved as first-line therapy for aortic stenting in the United States (Figs. 13.6 and 13.7). They can be used to effectively treat dissections, aneurysms, or ruptures of

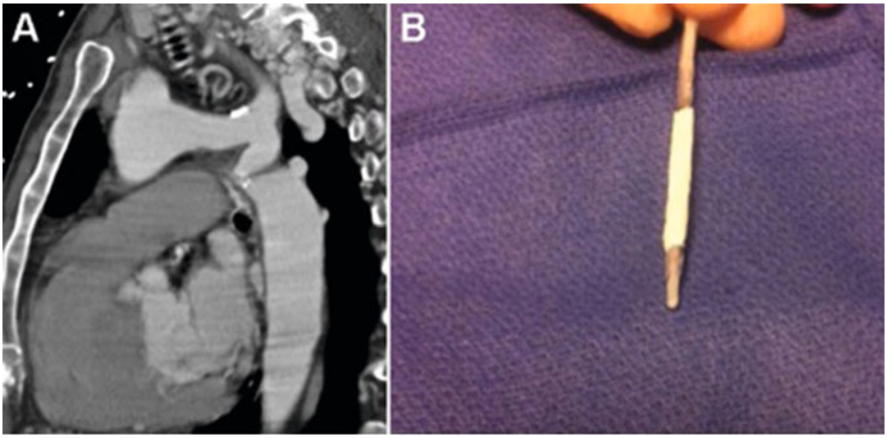

Fig. 13.6 (**a**) CT angiogram, sagittal view, demonstrating near interruption of the proximal descending thoracic aorta distal to the left subclavian artery in a 55-year-old man with coronary artery disease, multiple prior myocardial infarctions, and evidence of multiple arterial collaterals. (**b**) Balloon expandable covered stents are preferred to uncovered stents in order to minimize the risk of aortic rupture

the aorta caused during balloon angioplasty or uncovered stent deployment (Fig. 13.3). They are also strategic in cases with coarctation and a patent ductus arteriosus (PDA), where a covered stent would treat both, dilating the coarctation and occluding the PDA, as well as severe native coarctation or aortic interruption (Figs. 13.6 and 13.7) and older patients where there is a higher potential for dissection [85–91]. Careful positioning is critical to avoid occluding the spinal cord arterial branches, carotid arteries, and subclavian arteries (Fig. 13.3). The spinal cord branches originate at vertebra T9; this is oftentimes safely well below the level of the coarctation decreasing the risk of paraplegia, and pre-procedural imaging can help delineate the origin of the spinal cord vessels [92–94]. If occlusion of these branches does occur, perforation of the stent covering at the site of the branch can restore blood flow [24]. Other downsides to the use of covered stents include the need for larger sheaths, increasing the potential for femoral artery injury as well as the worse consequences of stent embolization with vessel occlusion such as with the renal and mesenteric vessels. Self-expanding stent grafts are widely used in aortic dissection and aneurysm formation in the adult population, and their use was extended in aortic coarctation, and some suggest that it is preferable in cases where there is an existing aneurysm and aortopathy, though it provides less radial strength compared to balloon expandable stents (Figs. 13.8 and 13.9) [92, 95, 96]. Multiple stent platforms can be utilized in sequence to achieve both coverage of aneurysms or dissections and adequate expansion of stenotic segments. For example, deployment of covered self-expanding stent grafts to cover an aneurysmal portion of the aorta followed by deployment of high radial force balloon mounted uncovered metallic stents can be used to provide greater radial force within the narrowed aorta (Figs. 13.8 and 13.9). The choice of stent ought to be individualized to the anatomy of each patient.

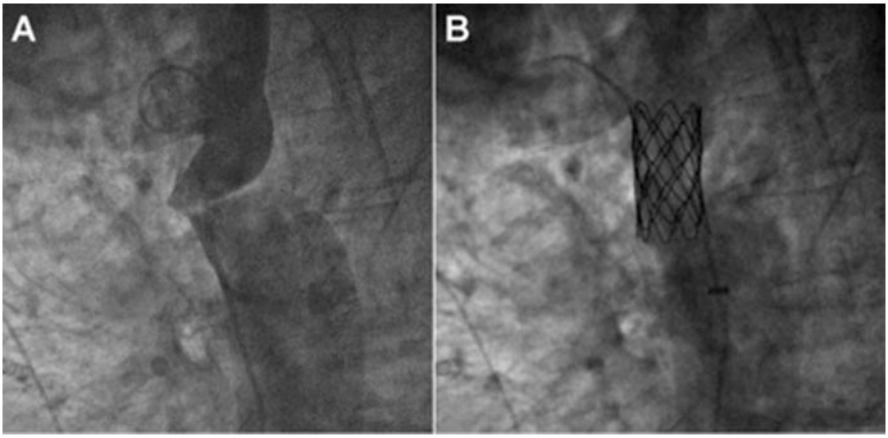

Fig. 13.7 The same patient from Fig. 13.5 with near interruption of the aorta. (**a**) Severe native coarctation noted on aortic angiography in a steep lateral anterior oblique view. (**b**) Resolution of the coarctation following deployment of a covered balloon expandable stent without evidence of aortic rupture or dissection

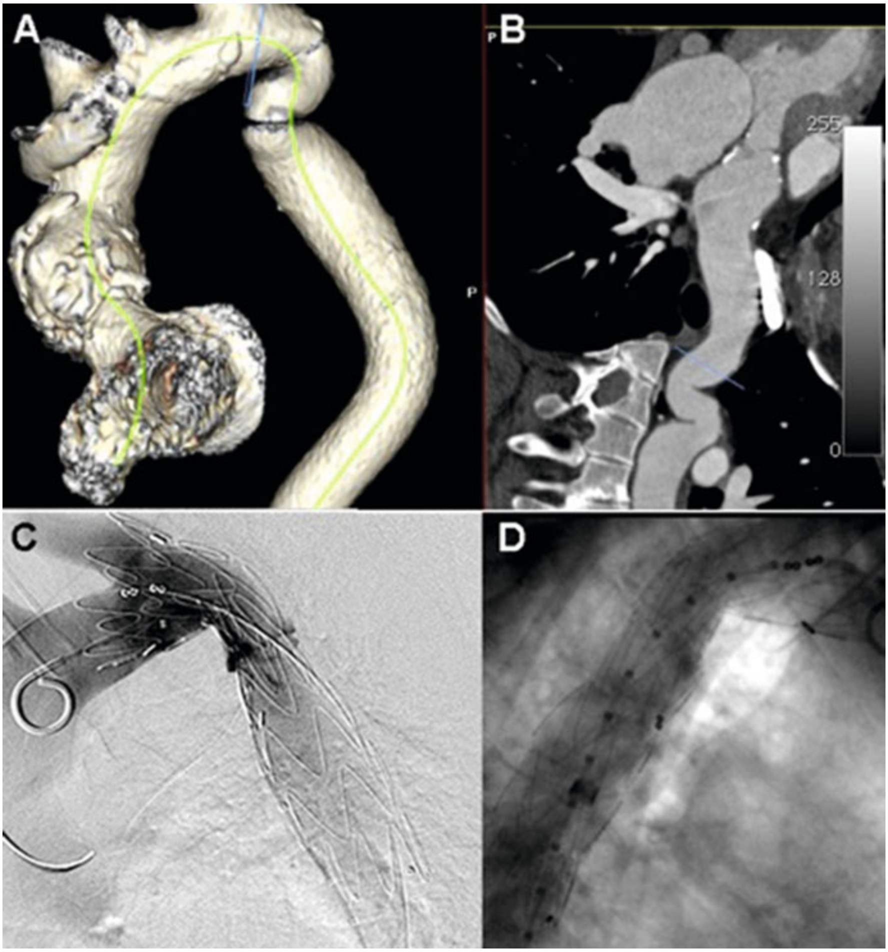

Fig. 13.8 (**a**) CT angiogram with 3-D volume rendering, left anterior oblique view, demonstrating a complex coarctation with severe tortuosity of the distal aortic arch and proximal descending thoracic aorta. (**b**) Multi-planar reconstruction of the aorta demonstrating the S-shaped tortuosity with multiple areas of stenosis. (**c**) Aortic angiogram with digital subtraction, left lateral view demonstrating a covered self-expanding stent graft within the distal arch and descending thoracic aorta with subsequent placement of a high radial force balloon expandable stent within the tortuous portion of the aorta. Note the resolution of aortic tortuosity and stenosis. (**d**) Aortic angiogram, right anterior oblique view, demonstrating resolution of stenosis and tortuosity

13.4 Complications

Complications of percutaneous interventions on aortic coarctation include dissection, rupture, aneurysm, pseudoaneurysm, and fistula formation at the arterial access site. It is important to remove the sheaths slowly to avoid avulsion of the

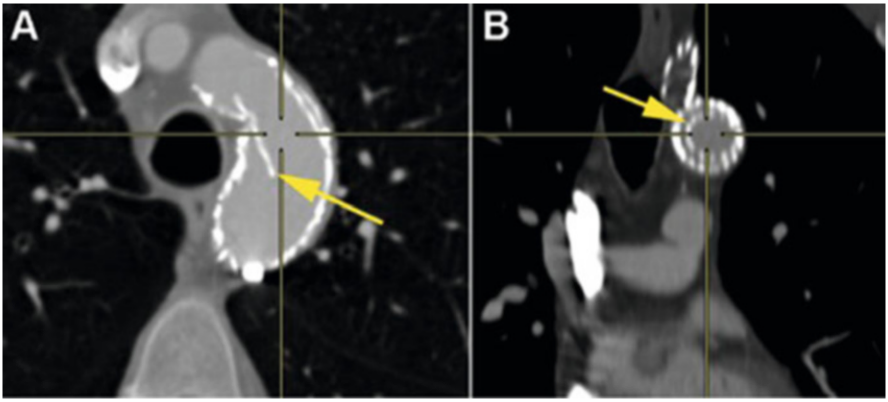

Fig. 13.9 (**a**) CT angiogram, axial view, demonstrating a self-expanding covered stent graft within the aortic arch and a high radial force uncovered balloon expandable stent (*yellow arrow*) within it at the site of the severest stenosis. This technique allows for aggressive dilation of severe and complex forms of coarctation using uncovered stainless steel stents within protective covered less rigid covered stent grafts. (**b**) Coronal view demonstrating the uncovered stent within the covered stent graft

femoral artery. Other complications include but are not limited to the following: stent migration, stent fracture, and thromboembolic complications. Paradoxical hypertension occurs more often in children, and less commonly compared to postsurgery [53, 48], and is managed medically. Endocarditis or aortitis is treated with intravenous antibiotics and usually does not require stent removal [82, 97–103]. Embolic stroke can also occur in up to 3.7 % of patients and can be minimized with antiplatelet therapy and meticulous care of wire, balloon, and stent positioning. Aneurysm formation may occur in up to 17 % of cases with uncovered stents; it is postulated that it's due to the medial injury during dilation; this incidence has decreased in occurrence with the use of covered stents. Pseudoaneurysm formation is associated with overdilation; this can be if stent dilation is limited to 70 % of the reference vessel diameter and less than 2.5 times the minimal luminal diameter at the site of coarctation. Fatal complications include aortic rupture; however, this complication can be managed with rapid placement of covered stents. Death from percutaneous intervention of aortic coarctation has been reported in 0–1.4 % of cases [26, 39, 51, 60, 87, 104–113]. An underappreciated adverse consequence of stenting is the insertion of a noncompliant, nonpulsatile stent in the aorta that can affect dynamic blood pressure control in the future [114–116].

13.5 Conclusion

Stenting is a significant advancement in the treatment of aortopathies, especially aortic coarctation. Stenting is the preferred method for management of aortic coarctation in adults and older children. The advent of covered stent platforms decreases the risk of serious complications such as rupture, pseudoaneurysm formation, and dissection.

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