Stenting Options for Coarctation of the Aorta

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KEYWORDS
- Coarctation • Angioplasty • Stent • Covered stent

KEY POINTS
- Surgery is the preferred intervention in neonatal period and infancy.
- Recaoarctation or aneurysm formation may be encountered during follow up. Complications include paradoxical hypertension, pleural effusion and spinal cord damage [in older patients].
- Balloon dilation for coarctation was the initial technique for transcatheter intervention. The use is controversial due to relatively high incidence of recoarctation and aneurysm formation. Complications include aneurysm formation, dissection and aortic rupture.
- Bare metal stent implantation for coarctation may result in less aortic wall injury than balloon angioplasty alone. Use is relatively safe and highly effective. Complications include aneurysm formation, stent malposition, stent fracture and vascular access injury.
- Covered stent implantation has a decreased incidence of aortic wall injury.
- Use is relatively safe and highly effective. It is the treatment of choice with coexistence of PDA or aneurysm, circumferential fracture of previously implanted stent, atretic/sub-atretic coarctation and older patients. Complications include stent malposition and potential side branch closure, vascular access injury.
- Technical considerations for stent implantation include: Implantation technique is challenging and demanding; Redilation over time is feasible; Long term follow up imaging is essential.

INTRODUCTION: NATURE OF THE PROBLEM
Coarctation of the aorta is a narrowing of the aortic lumen, usually of the thoracic descending aorta in the region just distal to the left subclavian artery. Although there are many variants of the anatomie position and length of the narrowing and associated lesions, such as a bicuspid aortic valve, hypoplastic transverse aortic arch, and aberrancies of the head vessels, the effect of the narrowing has the commonly shared features of increased afterload on the left ventricle, exposure of the upper body to hypertension, flow disturbance in the thoracic aorta, and decreased perfusion to the lower body.1,2 Overall coarctation accounts for approximately 7% of live births with congenital heart disease and can present in infancy, adolescence, or adulthood depending on the balance between the degree of flow disturbance and the compensatory mechanisms available to overcome it. Untreated coarctation has a poor prognosis with most patients suffering from significant morbidities associated with hypertension, including premature death due to heart failure, endocarditis, cerebral

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vascular accidents, and premature coronary artery disease.\textsuperscript{3} Despite successful treatment by surgery, balloon angioplasty, or stent implantation, the coarctation can recur from a variety of causes, including scarring, failure to match somatic growth, and tissue ingrowth.\textsuperscript{5–7}

Surgical repair of coarctation was first described in 1944\textsuperscript{9} and since then many techniques have been developed depending on the anatomy. These include resection and end-to-end anastomosis, patch repair, arch augmentation, and, less commonly, insertion of a bypass graft.\textsuperscript{9} Surgery is the preferred treatment of infants with coarctation and is successful; however, in older patients, complications are more common and can be severe, particularly when an adequate collateral circulation has not developed and spinal cord damage can ensue.\textsuperscript{9} Balloon angioplasty has been an acceptable technique for 3 decades for the relief of coarctation.\textsuperscript{10–12} It is successful in cases of recoarctation\textsuperscript{13} after surgical repair in infants but the use of this technique in native coarctations at all ages remains controversial due to the disruption of the intima and media of the aortic wall predisposing to a high incidence for future aneurysm formation.\textsuperscript{10–12} The aortic wall in coarctation is primarily abnormal and this is compounded by the flow disturbance over time so that in adult patients, tortuosity, thinning, cystic medial necrosis, and calcification may be present, further increasing the predisposition to dissection, aneurysm formation or even rupture.\textsuperscript{14}

Stent implantation for coarctation of the aorta has gained popularity since its initiation in 1991 with the rationale that overdistilation, dissection, and elastic recoil of the aorta are avoided with this technique and the pinning of the intimal flaps to the aortic wall after tearing of the intima and media promote healing.\textsuperscript{15–20} The stent can reinforce weakened areas within the aortic wall and provide a framework for neointima formation to cover the tear. These features of stenting result in less aortic injury than balloon angioplasty\textsuperscript{20} but dissection and aneurysm formation remain an important issue. Other complications of stent implantation include malposition, stent fracture, and femoral artery damage\textsuperscript{5–7} and their use is restricted to patients with vascular access of adequate size for the large delivery system, which is typically greater than 8\textsuperscript{2}\ for stents that can achieve an adult size of at least 18 mm. The implantation of stents of narrower maximal diameters may allow for smaller delivery systems and the treatment of infants and young children; however, the need for repeated reintervention to further dilate the stent to match somatic growth and the limited maximal diameter restrict the use of stents in this group of patients.\textsuperscript{17–19}

Covered stent implantation was initially introduced for the treatment of coarctation associated with aneurysms or a patent ductus arteriosus (PDA) and for tight or atretic native lesions.\textsuperscript{21–23} More recently, with the reasoning that the material cover supplements the advantages of bare stent implantation, providing additional protection to the acutely disrupted aortic wall and the downstream area of poststenotic dilation, the use of covered stents has broadened as the primary treatment of coarctation in some centers.\textsuperscript{24} The literature on the use of covered stents is encouraging but has been limited to small clinical series and case reports.\textsuperscript{21–27} These stents require larger delivery systems than bare metal stents and an additional limitation to use is the potential to jail important side branches, typically the left subclavian artery.

This article reviews the currently available options for stenting coarctation of the aorta, the equipment and techniques, and reported outcomes. This review is not intended to be comprehensive but to provide a practical framework for interventionists to approach the straightforward but challenging lesion of coarctation of the aorta.

INDICATIONS FOR TREATMENT

Coarctation of the aorta, native or recurrent, is diagnosed\textsuperscript{23,28,29} when the following are present:

- There is a difference in systolic blood pressure of 20 mm Hg between the upper and lower limbs.
- There are echocardiographic findings of coarctation, including 2-D imaging of narrowing in the descending aorta, a Doppler gradient with turbulence of color Doppler and persistence of the gradient into diastole, and an abnormal Doppler tracing with damping of the signal in the abdominal descending aorta.
- Hemodynamic evaluation demonstrates a peak-to-peak pressure gradient greater than 20 mm Hg.
- Imaging (aortography, CT, or MRI) demonstrates a significant narrowing in the descending thoracic aorta.

Although it is generally accepted that coarctation should be treated when a pressure gradient greater than 20 mm Hg is recorded, it has been suggested that milder obstructions and gradients may benefit from stent implantation by decreasing left ventricular diastolic pressure and preserving systolic and diastolic left ventricular function in the long term.\textsuperscript{32,34} Mild obstructions should be relieved when associated with hypertension at rest,
abnormal blood pressure response during exercise, progressive left ventricular hypertrophy, and in cases of complex heart disease, in particular Fontan palliations. The pressure gradient may be less than 20 mm Hg when a large collateral circulation is present or ventricular function is depressed.

Stenting reduces the gradient at the coarctation site more effectively than balloon dilation, and, therefore, the authors consider this technique in all patients in whom vascular access appropriate for the required delivery system is available. Exception is made in small children due to the need for repeated reinterventions to match somatic growth. The authors routinely stent patients with coarctation and who weigh more than 20 kg.

Covered stent implantation is indicated in patients with coarctation:

- Associated with aneurysm or degenerative changes of the aortic wall suggested by the presence of an aneurysmal ascending aorta or significant aortic tortuosity
- Associated with a PDA
- Critical or atretic obstructions
- Age over 18 years
- Aortitis, Turner syndrome, Williams syndrome
- Aortic wall injury (aneurysm, dissection, or rupture) after balloon dilation, bare stent implantation, or surgery
- Presence of circumferential fractures within a previously implanted stent in the aorta with malalignment or protrusion of the stent struts into the aortic wall on repeat angiography, MRI, or CT (Figs. 1–5).

Due to improvements in balloon and stent technologies, which afford lower profile systems and the encouraging results from recent reports, the authors now use covered stents as the first choice for treatment of coarctation of the aorta in suitable patients.

**STENTS**

A variety of types of stents are available for treatment of coarctation and can be divided into

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**Fig. 1.** (A, B) Lateral projection shows subatretic coarctation in 24-year-old adult with power injection of contrast below and above the coarctation. (C) Implantation of Advanta V12 LD covered stent on a 12-mm balloon. The delivery sheath is placed behind the partially inflated balloon to prevent movement during inflation. (D) Lateral view angiogram after further dilation to 16 mm 3 months after initial implantation.
groups depending on stent design, material, and size, each having advantages and disadvantages.

Balloon-expandable bare metal stents are the most commonly used and are made from stainless steel (Palmaz Genesis, Johnson and Johnson; Mega LD and Maxi LD series, ev3), platinum-iridium alloy (Cheatham-Platinum [CP] stent, NuMED), or chromium-cobalt alloy (AndraStent XL and XXL, AndraMed). The chromium-cobalt alloy is stronger than stainless steel and, therefore, thinner struts allow for a lower crimped profile without compromising radial strength. Closed cell stents are strong and rigid (Palmaz Genesis) and markedly foreshorten whereas open cell stents (Mega LD and Maxi LD), although weaker, foreshorten less, conform to the anatomy, and allow access to side branches. A hybrid open-closed cell stent (AndraStent) combines the advantages of these designs. Balloon-expandable expanded polytetrafluoroethylene (ePTFE)-covered stents are available in a closed cell design (CP stent) and open cell design (Advanta V12 LD, Atrium Medical) (Fig. 6).

Self-expanding bare nitinol stents have been reported in the treatment of coarctation of the aorta although their use is uncommon. Self-expandable stent grafts, which are commonly used for the endovascular treatment of thoracic aortic aneurysms, have been used in special circumstances usually when the degree of coarctation is mild and there is an aortic-bronchial fistula or large aneurysm when a balloon-expandable covered stent is inadequate. A self-expanding covered stent for aneurysm exclusion is probably safer than the balloon-expandable because it avoids an additional local vascular trauma caused by the radial forces of the balloon. These stents typically require a large delivery system of greater than 18F, have lower radial strength, and do not allow further expansion in the future.

The choice of stent depends on the coarctation anatomy and associated lesions, size of the patient, the experience and preferences of the operator, and availability. In the literature, and the authors' personal experience, balloon-expandable stents are the most commonly used for treatment of native and recurrent coarctation, and the interventionalist treating coarctation should be familiar with the properties of these stents.
The Palmaz XL 14-series stents can be dilated up to 25 mm, and are available in 30-mm to 50-mm lengths. They are laser-cut from a rigid stainless steel tube and shorten significantly during expansion and by almost 50% when expanded to their full diameter. Palmaz stents, with their closed-cell design, have little to no flexibility and do not conform to the contour of the aortic arch. The Palmaz Genesis XD stent is also laser-cut from stainless steel and the closed-cell design is modified by a sigma hinge interposed between the cells, which affords some flexibility around curves and also reduces the degree of shortening on expansion. The Genesis stents are available in multiple lengths but cannot be expanded further than 18 mm. This limitation makes the use of this stent inappropriate for larger aortas and patients. Unless the aorta is expected to reach a diameter significantly greater than 18 mm, the radial strength and flexibility of the Genesis stent make it a good option for treatment of lesions that lie across the curve between the transverse arch and the descending aorta. Concerns have been raised, however, with regard to fracturing when expanded to large diameters. R,39

The CP stent is composed of a 90% platinum and 10% iridium alloy, with the metal wires arranged in a zig pattern. Earlier versions of the stent were prone to fracture and refinements in the welding process using gold have been successfully used to minimize this problem. CP stents with 8 zigs can be expanded up to 25 mm and shorten less than the Palmaz stents, with the 39-mm and 45-mm lengths usually appropriate.23,26

The Maxi LD stent is made from stainless steel with an open cell design affording flexibility and reduces the risk of jailed side branches, making it especially useful in dilations of the transverse arch. In addition, when expanded in a staged fashion with progressively larger diameter balloons, it displays minimal foreshortening. The long-term resistance to fracturing, however, when expanded to 20 mm to 25 mm, is not known.38

The AndraStent XL and XXL stents are hybrid open-closed cell cobalt-chromium stents that can be dilated up to 25 mm and 32 mm, respectively, and are available in a variety of lengths. This combination of high radial strength with a lower profile, conformability, and minimized shortening make it a good candidate for the

Fig. 3. (A) AP aortogram after covered CP stent implantation for native coarctation. (B) AP aortogram after further dilation on follow-up with 14-mm balloon. There is an aneurysm on the medial aspect at the top of the stent and the stent is flared in to the aneurysm. (C) An Advanta V12 LD covered stent is dilated in the stent up to 14-mm to reach the base of the left subclavian artery. (D) The coarctation is dilated to 16 mm and the aneurysm is closed.
Fig. 4. (A, B) Right anterior oblique (RAO) and lateral aortogram of complex coarctation in 6-year-old girl with a right aortic arch, tight coarctation, and aberrant left subclavian artery. The right subclavian artery is enlarged because it is the major supply of collateral flow. (C, D) RAO and lateral aortogram after Genesis 1990 bare stent implanted and dilated to 9 mm. (E, F) RAO and lateral aortogram at 2-year follow-up demonstrating a small aneurysm on the RAO view. (G, H) RAO and lateral aortogram after Advanta V12 LD covered stent implantation on 12-mm balloon. The aneurysm is excluded and the stent dilated appropriately to the diameter of the transverse arch.
treatment of coarctation of the aorta, particularly in curved anatomy. Because this stent is new, the reported experience is encouraging but limited.36 There are 2 ePTFE balloon-expandable covered stents currently available. The covered CP stent is the standard CP stent covered with an ultrathin stretchable ePTFE membrane applied to a stent using biodegradable adhesives18,23 and is also available crimped and premounted on a BIB balloon (NuMed).

The Advanta V12 LD stent is a stainless steel open cell stent encapsulated by a covering of

Fig. 5. (A) Lateral projection shows severe coarctation and a small PDA in a 10-year-old boy. There is a small bronchial collateral. (B) Implantation of Advanta V12 LD covered stent on a 12-mm balloon with further dilation to 14 mm. The stent dilates the coarctation appropriate to the size of the transverse arch and closes the PDA.

Fig. 6. (A) Lateral projection shows mild coarctation at isthmus. (B) AP view—Rosen guide wire in right subclavian artery for stent implantation. (C) Guide wire in left subclavian artery with 6-mm balloon to align stent to wall of artery. (D, E) AP and lateral views with guide wire in ascending aorta so that the back end of the 14-mm balloon lays the stent down on the arch. (F) Stent dilates arch appropriately and flush with the native vessel walls.
ePTFE on the interior and exterior aspects. It is available in 3 lengths (29 mm, 41 mm, and 61 mm) and is premounted on high-pressure balloons of 12-mm, 14-mm, and 16-mm diameters. The stent can be incrementally dilated, by 4 mm at a time, to avoid tearing of the ePTFE, up to a maximal diameter of 22 mm.\textsuperscript{26}

In countries, such as the United States, where the availability of covered stents is limited, interventionalists have reported on the use of self-fabricated covered stents\textsuperscript{40,41} for high-risk patients or during acute aortic wall complications.

The major concern with the implantation of covered stents in the aorta is the risk of side branch occlusion, particularly of the left subclavian artery or the spinal artery, resulting in paraplegia. The major concern with the implantation of covered stents in the aorta is the risk of side branch occlusion, particularly of the left subclavian artery or the spinal artery resulting in paraplegia.\textsuperscript{42,43} The latter complication is usually avoided by not implanting a covered stent below the ninth thoracic vertebra. An additional concern with the use of covered stents is when distal migration occurs because the stent cannot be easily parked without occluding side branches and the origins of the renal and mesenteric arteries must be avoided.

**Balloons**

Balloon-expandable stents are available pre-mounted (as described previously) or need to be crimped on to a balloon for deployment. There are 2 types of balloon commonly used for deployment, single-balloon catheters (e.g., Powerflex [6–12 mm] and Maxi LD [14–25 mm]) and the BIB balloon (balloon-in-balloon) (NuMed). Single large-diameter balloons tend to expand first at their ends, which may predispose to stent movement if one end inflates before the other or balloon rupture if the stent has sharp edges. The BIB catheter is made from an inner balloon and a 1-cm longer outer balloon that is twice the diameter of the inner balloon and they are available in outer-balloon sizes of 8 mm to 24 mm. They offer the important advantage of opening the stent more uniformly along its length, resulting in more control over its precise placement and preventing stent flaring and migration; however, they are more bulky than their single counterparts. The choice of balloon depends on the coarctation anatomy and dimensions, the stent to be implanted, and operator preference and experience. One author (EB) always uses single balloons whereas the other (CACP) uses the BIB for special cases. Single-balloon catheters are preferable in smaller patients to reduce risk to the femoral artery at the access site, whereas the BIB balloon is helpful in precise positioning in transverse arch stenting. On occasions, high-pressure balloons, such as the Mullins balloons (NuMed) and Atlas balloons (Bard), may be needed to dilate up a residual waist, particularly in postsurgical coarctations. Generally, a balloon that is slightly longer (approximately 1 cm) than the stent is used for implantation.

**Technique**

The implantation techniques for bare and covered stents in coarctation of the aorta vary among institutions and depend on the anatomy of the coarctation and materials used.\textsuperscript{15–41} Despite this variation, there are several steps that are common to all coarctation stent procedures:

- Vascular access
- Crossing the lesion
- Hemodynamic assessment
- Definition of anatomy by aortography
- Measurement of diameters of transverse arch, isthmus, coarctation, and descending aorta at the level of the diaphragm and length of aorta to be dilated
- Guide wire positioning
- Sheath advancement
- Stent implantation, positioning, and dilation
- Assessment and postdilation
- Sheath removal

The procedure is generally performed under general anesthesia because it is painful and patient movement at the time of stent deployment can be hazardous.

**Vascular Access**

After obtaining percutaneous femoral arterial access, a hand injection of contrast media should be performed through the sheath to assess the size of the vessel and, if of appropriate size, for the delivery sheath. A second vascular access may occasionally be used for serial angiograms in order to assist proper positioning of the stent during deployment and this may be achieved transseptally through a femoral vein or using a radial or brachial artery. A second access is indicated for more complex cases, such as transverse arch stenting, subatretic coarctation, and when an aneurysm is present.\textsuperscript{17} Venous access may also be required if rapid right venricular pacing is useful for stent positioning. This is of importance when stenting the aortic arch or using covered stents in proximity to head vessels or when significant
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aortic regurgitation, creating large pressure swings, is present. After vascular access is obtained, heparin sulfate (100–150 IU/kg; maximum 10,000 IU total) is given intravenously and the activated clotting time (ACT) should be maintained at greater than 200 seconds. The authors administer intravenous antibiotics prior to stent implantation.

Crossing the Lesion

The lesion is typically crossed from the descending aorta with the aid of a shaped (Berenstein or Cobra) end-hole catheter and a hydrophilic guide wire. Subaortic lesions are often more easily crossed from above, with the anatomy creating a funnel, which guides the tip, and this can then be snared and exteriorized through a femoral sheath below. In patients with atretic coarctation, a discrete atretic segment may be perforated from above or below using a transseptal needle, stiff end of a coronary wire, or a radiofrequency catheter.

Hemodynamic Assessment

The peak pressure gradient is assessed via simultaneous measurements above and below the lesion or by pullback across the lesion if it was easy to cross. The pressure gradient may be less than that measured by arm-leg cuff blood pressure due to the use of general anesthesia lowering the systemic vascular resistance and this can be rectified with fluids and medications to create a stable state. Extensive collateral flow may also reduce the peak gradient. In these situations, the indication for intervention should be based on the clinical, echocardiographic and angiographic findings.

Aortography and Measurement

Aortic angiograms are typically obtained in the anteroposterior (AP) and lateral projections or using shallow left anterior oblique or shallow right anterior oblique projections with caudal angulation. A high-volume, rapid injection in the region of the coarcted segment using a 5F marker pigtail (eg, Merrit Medical) catheter usually suffices to define the anatomy and enable accurate measurements of the diameters of the transverse arch, aortic isthmus, coarctation, poststenotic dilatation, and descending aorta at the level of the diaphragm. The recent introduction of 3-D rotational angiography in to the pediatric cardiac catheterization laboratory provides an additional tool to understand complex coarctation anatomies. The rotation provides multiple individual frames of the aorta, each from a different angle, which affords a more detailed assessment of the spatial anatomic relationship between a coarcted segment and the implanted stent or associated aneurysm than that obtained from a standard biplane view.

The initial stent diameter chosen should at least match the diameter of the aorta adjacent to the coarctation for it to anchor well. The final stent diameter should be similar to that of the isthmus or distal transverse arch. In coarctations in which there is a large degree of mismatch, initial relief should be provided at a diameter that the stent is well opposed and stable. Further dilation to the final diameter can be performed some months later. The use of covered stents in this setting adds extra protection to the aortic wall.

The length of the aorta to be stented should be measured from above the region of tapering proximal to the coarctation to well into the poststenotic dilation. This is important to avoid the distal edge of the stent touching the aortic wall here to avoid dissection. In long lesions requiring 2 or more stents, it is important to telescope the stents with sufficient overlap so they can be dilated together and not come apart because the stent edge is forced in to the aortic wall and the risk of dissection is increased. With covered stents, the length is decided on with the above considerations and taking in to account the position of side branches. In the poststenotic dilation area, the covered stent deflects the flow away from the wall toward the center. The anatomy needs to be carefully assessed for the presence of aneurysms/dissections, especially in patients with recoarctation after previous intervention.

Guide Wire Positioning

Prior to intervention, a long support wire with a soft tip, such as a 280-cm 0.035" Rosen wire or Amplatz Super Stiff Guide Wire, is parked in the ascending aorta or right or left subclavian artery, depending on the straightest wire course and angulation of the lesion. The softer Rosen wire does not distort the anatomy and usually provides sufficient support for advancing of the sheath and stent implantation. The distal position of the tip of the wire is changed during the procedure if the stent needs to be shaped to match the aortic contour (see Fig. 6). It is important not to place the wire in the left subclavian artery if the balloon for stent implantation enters the artery because the oversizing of the artery by the tip of the balloon can damage the artery or, alternatively, the balloon milks downwards and changes the position of the stent.

Sheath Advancement

A popular sheath for stent delivery is the 75-cm long Cook RB-Mullins sheath (Cook Cardiology),
which has a radiopaque tip and a sidearm for contrast injections and pressure measurements. The French size of the long sheath required for stent implantation depends on the profile of the balloon and generally needs to be 1F to 2F larger. When using a covered CP stent, the sheath may need to be 2F to 3F larger than the implanting balloon. The Brite Tip 55-cm sheath (Cordis) is a useful sheath, especially in the smaller patients when a delivery system of up to 9F is required. The sheath is advanced over the wire through the lesion and the dilator removed. A hand injection of contrast through the sideport is useful for establishing the site for implantation with relationship to anatomic bony landmarks.

**Stent Implantation, Positioning, and Dilation**

If the selected stent is not premounted, it is manually crimped on to the chosen balloon. A piece of umbilical tape looped around the stent and pulled at both ends to help tighten the stent onto the balloon may be used, especially when crimping larger profile stents on to small diameters in balloons. During crimping, the guide wire should be left in the catheter-balloon shaft in order to straighten the system and avoid damage to the balloon and crushing of the shaft. Manual crimping of the covered CP stent onto the catheter balloon and loading it into the long sheath requires extra care. Wetting of the ePTFE layer should be avoided so that it keeps its original shape around the stent, preventing unfolding and damage. A cutoff short sheath (with the same profile of the long sheath) is used to protect the covered CP stent while advancing it through the hemostatic valve and to prevent it bollowing.

The balloon-stent assembly is back-loaded into the sheath and advanced to its tip. The sheath is slowly retracted, exposing the stent in the vascular lumen. Repeat angiograms via the side arm of the long sheath during retraction or via a second angiographic catheter positioned in the arch are performed to ensure proper stent position prior to balloon inflation.

Although the use of the BIB balloon can facilitate precise stent deployment, additional maneuvers can also be used. Reduction of the pulse pressure in a controlled manner by rapid right ventricular pacing at 180 bpm 220 bpm during stent deployment is useful, particularly in transverse arch stenting. The rate of pacing varies between 180 and 220 beats per minute and the exact rate is determined at the outset by monitoring the pressure in the ascending aorta while pacing the heart at different rates. The rate for pacing that reduces the pulse pressure in the aorta is used. The authors often use the sheath to buttress the balloon, once inflated, to prevent it being pushed down to the descending aorta with the predilation of the lesion is controversial and has been associated with a higher incidence of aortic wall abnormalities at follow-up in the report from the Congenital Cardiovascular Interventional Study Consortium (CCISC) multicenter study. In the presence of a critical lesion, however, the coarctation may be predilated using a 5-mm to 6-mm diameter balloon, just to make enough room for the passage of the long sheath. Predilation of the coarctation is a prerequisite in the Coarctation of the Aorta Stent Trial (COAST) protocol (http://clinicaltrials.gov/ct2/show/NCT00552812). From the authors' viewpoint, although postsurgical lesions may be noncompliant, almost all native coarctations, except those that are part of a middle aortic syndrome, are compliant and do not need to be routinely predilated. When using the BIB balloon, the inner balloon is inflated first and the stent repositioned, if needed, before inflation of the outer balloon. Most patients require only 1 or 2 dilations for stent deployment and it is recommended that the second inflation of the outer balloon is performed while keeping the inner balloon deflated because the dilation force is better distributed in this way.

The authors have described a method for covered CP stent implantation using the lowest profile system possible by anchoring the stent in the coarctation with an 8-mm to 10-mm high-pressure single balloon and then carefully removing this balloon and further dilating the stent through the same sheath with a Maxi LD balloon. The authors have managed to implant and dilate stents up to 16-mm in this way, on a regular basis, using a 9F Brite-Tip 55-cm sheath. The low-profile Advanta V12 LD stent can be implanted on a 12-mm balloon through an 8F sheath (manufacturer's recommendation is 9F) and the 14-mm and 16-mm delivery systems need an 11F sheath. The methods for implantation are similar to those described previously.

**Assessment and Further Dilation**

After implantation, the pressure gradient is measured and aortography performed to assess the stent position, adequacy of dilation, and presence of aortic wall complications. Further dilation of the stent can be performed during the current procedure or scheduled at a later date when there is a large mismatch of initial size of coarctation to the diameter required. When using a covered stent, the authors try to dilate the stent so that the covering is apposed to the dilated aortic wall immediately adjacent to the coarcted segment to
maximize the protection of the ePTFE in preventing aneurysm formation. Although some investigators have advocated flaring the ends of stents to optimize endothelialization,\textsuperscript{45} it is unlikely that complete stent apposition in the poststenotic region can be achieved without distorting the stent, and this may be detrimental to stent stability without any evidence that it is necessary. The main goal of stenting coarctation is for gradient relief and this is attained regardless of complete apposition of the stent in the poststenotic area. With covered stent implantation, the flow in the poststenotic area is contained within the stent and directed toward the lumen and not the aortic wall, thereby protecting the wall. The formation of clots between the stent and aortic wall in the poststenotic area has not been reported\textsuperscript{46,47} or found in the authors’ experience.

After stent deployment, care should be taken to not dislodge the stent. Once the balloon is deflated, the sheath is gently advanced over it, followed by balloon withdrawal.

Excessive catheter and wire manipulation over the recently stented area should be avoided; however, if needed to match the aortic contour, the stent can be shaped by the same or additional balloons (as seen in Fig. 6).

**Sheath Removal**

When the ACT is prolonged (>200 s), the effect of can be partially neutralized using protamine. A Perclose or Prostar (Abbott Vascular) suture has been used to close the arteriotomy but needs to be inserted in the femoral artery prior to the introduction of the large sheath. This method helps achieve hemostasis quickly at the end of the procedure and prevent hemorrhagic complications at the puncture site.\textsuperscript{50} Occasionally 2 sutures are needed to repair the artery, especially when a large (14F) sheath is used. Reliable hemostasis can usually be achieved, however, by judicious manual compression.

Patients are usually discharged home the following day on aspirin (5 mg/kg/d; maximum 300 mg) and instructed to avoid contact sports for 6 months. A chest radiograph, a 12-lead electrocardiogram, and a transthoracic echocardiogram are obtained before discharge and scheduled after 1 to 3 months, 6 months, 12 months, and yearly thereafter along with the clinical visits.

Due to the possibility of late aneurysm formation after stenting, follow-up imaging is mandatory in all patients.\textsuperscript{46-50} Therefore, a repeat catheterization, MRI, or CT should be scheduled approximately 12 months after the procedure and probably at fixed periods during the patient’s lifetime, especially before and after pregnancy. Elective recatheterization is performed after 6 to 12 months to carry out stent redilation when there is residual stenosis as a result of the stent having been intentionally underinflated initially.\textsuperscript{51,52}

**OUTCOMES**

Since the first cases of coarctation stenting were reported in the 1990s, the encouraging outcome of this procedure has been described in a considerable number of individual series reporting both short-term and intermediate-term results.\textsuperscript{5,6,15-19} In 2007, one large multicenter retrospective series\textsuperscript{8} was reported by the CCISC on 565 procedures of stent implantation performed in 555 patients with coarctation between 1989 and 2005, of which 553 (97.9%) were successful in reducing the gradient to less than 20 mm Hg. Among the successful cases, there was a mean reduction of the peak-to-peak gradient from 31.6 ± 16.0 to 2.7 ± 4.2 mm Hg, a mean increase in diameter from 7.4 ± 3.0 to 14.3 ± 3.2 mm, and a mean increase in the ratio of the coarctation of the aorta diameter to the descending aorta diameter measured at the level of the diaphragm (CoA:DAO) from 0.43 ± 0.17 to 0.85 ± 0.15. These results, showing a high degree of success, are similar to those reported in other smaller series.\textsuperscript{15-19} These series and the CCISC in a follow-up study reported that the relief of the pressure gradient persisted in the majority of patients at medium-term follow-up.\textsuperscript{6} Significant pressure gradients on follow-up were associated with suboptimal/restricted expansion of the stent at the time of implantation, stent recoil, and neointimal growth within the stent. In-stent restenosis was associated with a smaller poststenotic diameter and a higher poststenotic systolic gradient and in the main this occurred in those of a younger age and lower weight at the time of implantation.\textsuperscript{5,6,47} This is, as expected, due to the vascular lumen being larger in the adult aorta and a mild intrastent proliferation usually does not result in flow obstruction and local gradient generation. The stents could be dilated further in most instances to resolve these issues, although questions have been raised as to the feasibility, safety, and effectiveness of redilation.\textsuperscript{50,51} It is the authors’ experience and that of others that both bare and covered stents can be successfully redilated late at follow-up with no untoward effect.\textsuperscript{52}

The efficacy of coarctation stenting is, therefore, high but the safety of the procedure has been a cause of concern with significant complications occurring in 14.3% of cases in the CCISC acute
study. The complications were broadly divided into the technical and aortic wall categories. Technical complications included stent migration, stent fracture, and balloon rupture and occurred in 10.9% of cases whereas acute aortic wall complications included intimal tears, dissection, and aneurysm formation and were present in 3.9%. These complications were treated by conservative, transcatheter methods, including the implantation of additional stents or surgery. Unfortunately, 2 of the patients died after having suffered severe neurologic damage. The investigators noted that there was a significant decrease in technical complications after January 2002 and related this to improvements in catheter and stent technology (eg, sharp-edged Palmaz 8 series stents causing balloon rupture), providing the interventionists with greater options, and, in addition, "a learning curve phenomenon could not be excluded."

In the intermediate follow-up CCISC study, 144 of 578 (24.9%) patients had follow-up imaging (CT, MRI, or aortography) of whom 18 of 144 (12.5%) had an aneurysm or developed a dissection/intimal tear. Most aneurysms were small and were managed conservatively although 4 patients required further intervention, such as the implantation of a covered CP stent. The results reported in the CCISC studies are of particular interest with reference to the results reported by Chakrabarti and colleagues on 88 patients with coarctation who underwent 102 stent procedures from 2002 to 2008. There were 4 acute complications (3.7%) of which 2 (1.9%) were aortic wall related. A follow-up CT was performed on 95.1% of the patients of whom only 1 developed an aneurysm associated with restenosis of a stent that had fractured. This was successfully treated with a covered stent.

Chakrabarti and colleagues have similar percentages of native coarctations in their series and used the same definition for aneurysm formation. Therefore, the marked differences in the rates of aneurysm formation between the groups may be explained by the small percentage of the CCISC cohort who underwent follow-up imaging. This imaging was presumably performed due to clinical concerns and, therefore, the group is probably unrepresentative and biased. Another observation, however, is that in the CCISC group, 14 of 511 (2.7%) stents implanted were covered as opposed to 26 of 94 (27.7%) of the stents used in Chakrabarti and colleagues’ series.

The use of covered stents for coarctation has gained popularity after an initial case report and small series in treating native and recoarctations associated with, or at risk for, aneurysms. A larger experience was published by Ewert and colleagues, in 2005, with the use of the CP stent in a broad spectrum of heart malformations, of which 37 had coarctation and 11 of these were successfully treated with covered stents. The indications included subatretic or severe lesions, aneurysm formation, and previously implanted stent fracture. All stents were placed in the lesion without complications. During follow-up, one covered stent fractured at 6 months and required the implantation of an additional covered stent. Similarly, in 2005, the authors’ group (CACCP) in Sao Paulo, Brazil, reported on 9 patients with coarctation who received covered stents (10 CP stents and 2 self-expandable Braile stent grafts). The indications included severe or atretic coarctation, aneurysm formation, a coexistent patent arterial duct, and circumferential fracture of a previously implanted stent. Median age and weight were 31 years and 65 kg, respectively, and the procedure was successful in all subjects. However, 2 patients developed aneurysms, 1 requiring conservative management and the other successfully treated using a second covered custom-made self-expandable Braile stent. During follow-up, all patients had either reduced the dose or suspended the use of antihypertensive drugs.

After these early experiences several larger series were reported of 30 to 40 patients who underwent implantation of covered stents for mainly complex coarctations with aneurysms, previous stent-related complications, recurrent coarctation after surgical treatment, aortobronchial fistula, previous stent fracture, an associated patent arterial duct, or coarctations at risk of because of complex coarctation anatomy or advanced age. All series reported a significant reduction in pressure gradients and improvement in the coarctation diameter with a low rate of acute complications. When available, short-term follow-up with imaging, including CT, MRI, and aortography, demonstrated maintained position and patency of the stent and exclusion of aneurysms present at the time of implantation.

In light of this success in complex coarctations, the authors (EB) decided to implant covered CP stents in simple native coarctations in order to potentially benefit from the additional protection of the material covering the aortoly disrupted aortic wall in the short term and protection of the dilated segment and the downstream area of poststenotic dilation in the long term. Initially, to create a small delivery system of 9F to 10F, the authors implanted the stents on balloons of diameter just sufficient to anchor the stent in the coarctation site and then performed subsequent serial dilations with
larger diameter balloons until the pressure gradient was less than 20 mm Hg and the stent was apposed to the aortic wall; 22 patients with native coarctation were treated successfully with no complications and 9 patients underwent further dilation at an average of 5 months later. Complications included a small tear at further dilation, which was treated with a second stent and a femoral pseudoaneurysm treated conservatively. At short-term follow-up, all patients were alive and well with no evidence of recoarctation or aneurysm.

Recently, the authors and colleagues50 reported the acute results on 25 patients with coarctation treated in a similar manner with the large diameter covered Advanta V12 premounted stent placed through 8F to 11F delivery systems. The technique again included an initial inflation on balloons of a diameter sufficient to anchor the stent in the coarctation site using the smallest available delivery system followed by a secondary dilation using larger diameter balloons until the pressure gradient was less than 20 mm Hg and the stent was apposed to the aortic wall. The procedure was successful in all patients with the stent reaching the planned diameter and there were no complications. Median follow-up was 4.9 months with no complications or evidence of recoarctation.

These series, and other recent reports,54-56 have shown good procedural and midterm safety and effectiveness of stent implantation for coarctation. These reports are retrospective analyses, however, and are limited by nonrandomized study design, small sample size, absence of systematic prospective data collection, and planned follow-up imaging.57

Follow-up imaging is of paramount importance to the evaluation of the outcomes for coarctation interventions, including surgery. Apart from Chakrabarti and colleagues' series59 and a smaller one by Tanous and colleagues,54 however, there are no large studies with complete long-term imaging and, therefore, the true incidence of aneurysms is unknown. Imaging is complicated by the presence of the stent, which causes artifact in the MRI, making the evaluation of in-stent stenosis and stent fracture impossible.50 MRI black blood imaging can be used to evaluate aneurysms, stent position, and dissections extending beyond the stent but there are a limited number of centers that can perform these procedures on a routine basis. CT scanning is quick and produces high-quality images but carries a significant radiation dose. If serial scans are performed during a patient's lifetime, the accumulated radiation dose is prohibitive. Aortography is usually confined to patients requiring reintervention and is both invasive and involves exposure to radiation.

A recent editorial59 suggested 3 to 5 yearly follow-up by MRI imaging and that if the scan is suggestive of a complication, then a CT scan or direct evaluation by catheterization is performed.

There are currently 2 ongoing prospective clinical trials to evaluate the safety and efficacy of covered stenting for coarctation of the aorta: the COAST II trial (NCT01278303) and the Large Diameter Advanta V12 Covered Stent Trial for Coarctation of the Aorta (NCT00978952). The results of these trials are eagerly awaited.

FUTURE PERSPECTIVES

Future directions in stent design should include a reduction of the stent profile while maintaining radial strength, flexibility, and maximal expandable diameter to prevent injury to the vascular access site and development of recapturable and repositionable devices as well as the capability of the stent to adapt to somatic growth (growth stent).58 Biodegradable stents59 may provide an alternative treatment of coarctation in infants.

SUMMARY

Stent implantation for native or recurrent coarctation of the aorta has progressed from an acceptable alternative to surgical therapy to be the primary intervention in older children, adolescents, and adults in many institutions. Stents have proved highly effective for intermediate-term relief of the obstruction and covered stents, and, in particular, may minimize the incidence of aortic wall complications. Although the implantation technique can be challenging and demanding, it is safe in experienced hands. Follow-up imaging is essential on a long-term basis to assess for aortic wall damage, in particular aneurysm formation. Reinterventions, including further dilations to match somatic growth, and additional stent placement are often required.

REFERENCES


