Cardiology in the Young (2016), **26**, 1563–1567
doi:10.1017/S1047951116001694

Original Article

Transcatheter intervention for coarctation of the aorta*

Matthew E. Zussman,[1] Russel Hirsch,[2] Carrie Herbert,[3] Gary E. Stapleton[3]

[1]*Florida Hospital for Children, Orlando, Florida;* [2]*The Heart Institute Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio;* [3]*Johns Hopkins Heart Institute, All Children's Hospital, St. Petersburg, Florida, United States of America*

Abstract

Keywords: Cardiac catheterisation; balloon angioplasty; coarctation of the aorta; stent placement

Received: 29 August 2016; Accepted: 5 September 2016

Coarctation of the aorta is a relatively common form of CHD, with an estimated incidence of three in 10,000 live births, and accounts for ~5% of all cases of CHD.[1,2] The lesion was first eloquently described by Giovanni Morgagni, and the first surgical intervention was performed by Crafoord in 1944.[3,4] Although there has been a fascinating evolution of surgical techniques for the treatment of coarctation, we limit the scope of this review to catheter-based options. Balloon angioplasty of the aorta was first described by Singer in 1982 and by Lock et al in 1983.[5,6] Since then significant controversy has surrounded this interventional method for the treatment of coarctation, especially for native lesions. Nine years after balloon angioplasty for coarctation was introduced, the first endovascular stent placement was reported.[7] Since then, the endovascular stent technique has evolved via improved technology and multi-institutional studies. In recent times, results on covered stents have become available, and larger studies are ongoing. We will review the catheter-based options for treatment of coarctation of the aorta, including the history of these procedures, technical considerations, available data, and future contemplations.

Early history

From the mid-1900s until the first reported balloon angioplasty, treatment for coarctation was exclusively surgical. This progressed from circumferential end-to-end anastomosis, prosthetic patch, subclavian flap, interposition graft, to extended end-to-end anastomosis.[8–11] In the early 1980s, angioplasty was reported for the treatment of coarctation. Since its first report, multiple studies have shown that, although acute results are promising, late complications have prevented this treatment from being the modality of choice in native coarctation. Another catheter-based intervention was needed, and endovascular stent placement for coarctation was reported in 1991. Since then, there have been multiple modifications to this therapy, including changes to technique, mounting balloons, and the stents themselves, which have made this modality more applicable to the paediatric population. The early experience with catheter-based techniques has driven the field towards improved options, with better results and lower rates of procedural complications.

Technical considerations

Percutaneous interventions of the aorta are usually performed via a retrograde approach following femoral arterial access. Other options include an antegrade approach via venous access and a transseptal catheter course. Access from a carotid cut-down or percutaneous carotid approach has been reported.[12,13] The procedure should be performed under

*Presented at the Johns Hopkins All Children's Heart Institute 16th International Symposium on Congenital Heart Disease, Special Focus: Pediatric and Congenital Diseases of the Aorta, Co-Sponsor: The American Association for Thoracic Surgery (AATS), Saint Petersburg, Florida, United States of America, Saturday 13 February, 2016 to Tuesday 16 February, 2016.

Correspondence to: M. Zussman, MD, Florida Hospital for Children, 2501 N Orange Ave Suite 310, Orlando, FL 32804, United States of America. Tel: 407 303 2001; Fax: 407 303 2450; E-mail: matthew.zussman.md@flhosp.org

general anaesthesia as stretching and/or tearing of the aortic wall is painful and could cause patient movement at a critical point. Haemodynamics are typically performed by direct pullback across the area of interest. Angiography of coarctation is best highlighted with a biplane system, the anteroposterior camera at 0°, or left anterior oblique with the lateral camera at 90°. This is usually performed with a marker catheter for accurate calibration to precisely assess the size of the normal portion of the aorta as well as the minimal lumen diameter. Multiple advances in imaging, including three-dimensional rotational angiography with image overlay, MRI overlay, and/or MRI-based intervention, have been described. As coarctation is an anatomically heterogenous lesion, proper imaging will help in the planning of the intervention, including determining the wire position, balloon size, and stent type and size. Balloon/stent size is usually determined by the diameter of the normal portion of the transverse aortic arch or the aortic size at the level of the diaphragm.

The decision to move forward with an aortic intervention will typically follow the American Heart Association's published guidelines for catheter intervention of coarctation.[14] Once the diagnostic portion of the case is complete, it is important to gain a stable wire position. A stiff wire with a floppy tip is preferred to help stabilise the balloon during inflation while lowering the risk for distal wire injury. Wire position options include the left ventricle, the ascending aorta, or the right subclavian artery. Although the right subclavian artery may offer more stability, it carries a slightly increased risk of dissection of the innominate artery.[15] To further increase the stability of the balloon, rapid right ventricular pacing can be used, especially in older patients with higher stroke volumes.[16] A ventricular rate that causes at least a 50% reduction in systolic blood pressure is preferred.

After obtaining adequate wire position and aortic measurements, a balloon is selected for angioplasty. A low-pressure balloon can be used initially to better understand the compliance and narrowing of the vessel. If inflation with the low-pressure balloon is not therapeutic and there is a significant residual waist, a higher-pressure balloon can be used. Serial dilation with larger balloons can be performed; however, a pullback gradient and angiogram to assess the response and any vessel wall injury should be performed. The largest balloon used is limited to the size of the adjacent aorta or, historically, to three times the minimal lumen diameter of the aorta coarctation site.

Stent placement in the aorta requires even more attention to balloon stability and accurate angiographic measurements (Fig 1). There are mixed opinions regarding compliance testing with a low-pressure balloon before stent placement to avoid vessel wall injury. If there is a waist on the compliant balloon at full inflation, a smaller balloon is used to mount the stent, with intention to return at a later date for further dilation.[17] Stent selection, including bare metal versus covered, depends on the size, location, and complexity of the narrowing. There are many options for use as mounting balloons; however, the Balloon in Balloon™ (NuMed, New York, United States of America) allows for more uniform stent dilation and significantly decreases the risk for stent displacement during inflation. This balloon does require a larger sheath limiting its use in smaller patients. A long sheath is used and placed past the coarctation site. The mounted stent is placed across the narrowing, the sheath is pulled back, and hand injections of contrast are used to confirm stent position before deployment. Rapid ventricular pacing is initiated, if desired, and the stent is deployed. Post intervention, pullback and angiography is performed and further dilation of the stent can be performed if indicated. Post-implantation modifications have been described, including flaring the ends of the stent for better apposition to the aortic wall, dilation of the cells of a bare metal stent to head/neck branch vessels, and puncture of covered stents to restore flow to the left subclavian artery.

Outcomes

Balloon angioplasty for native coarctation

Multiple studies performed in the 1990s through the early 2000s report adequate acute and mid- to long-term efficacy of balloon angioplasty for native coarctation with acute success rates as high as 100%.[18–21] In 2014, the Congenital Cardiac Intervention Study Consortium (CCISC) published its multi-centre data on 76 patients who had undergone angioplasty of native coarctation.[22] Overall, 73% of patients left the hospital with upper- to lower-extremity blood pressure gradient <15 mmHg. Acute vessel wall injury was reported in 11% of patients. When combining two of the larger studies there was no procedural mortality in 143 patients.[20,22]

Although the acute outcomes appeared promising, there was growing concern over the long-term results of angioplasty for native coarctation. The rate of recurrent coarctation is reported to be between 15 and 25% in all patients and as high as 83% in neonates.[20] The accepted mechanism of action of angioplasty includes disruption of the vessel wall; therefore, it is not surprising that the rate of wall injury is reported at 25–43%.[22,23] Overall, in the CCISC cohort, there was a 57% total complication

https://doi.org/10.1017/S1047951116001694 Published online by Cambridge University Press

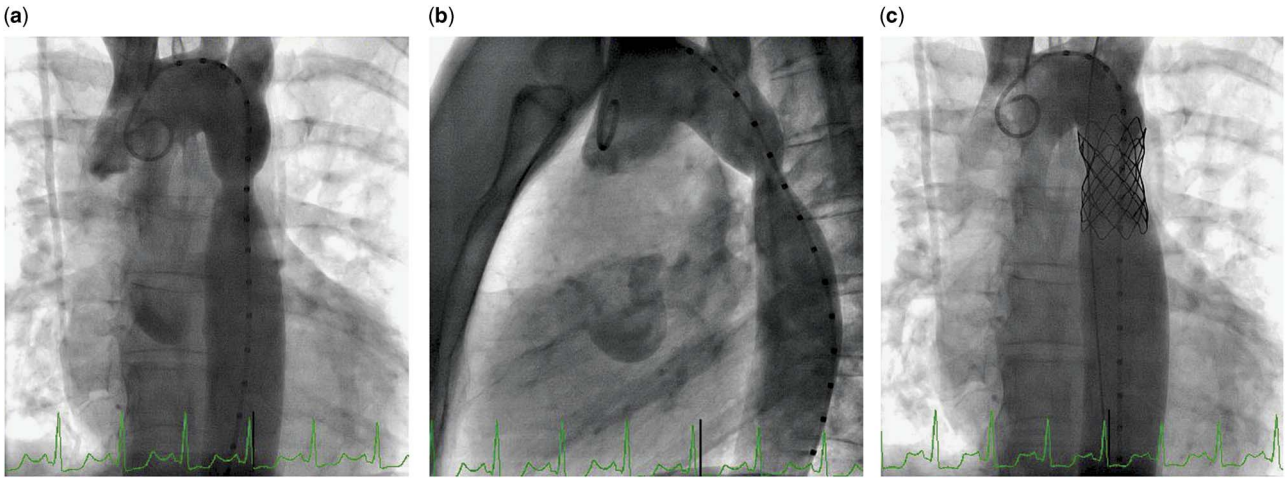

Figure 1.
*Stent implantation in an adult patient with coarctation of the aorta. (**a**) Anterior and (**b**) lateral projections showing coarctation of the aorta distal to the take-off of the left subclavian artery with ~50% narrowing. (**c**) Angiogram post-implantation of a Cheatham-platinum covered stent demonstrating a well-positioned stent with improved diameter of the aorta and no evidence of aortic wall injury.*

rate at intermediate-term follow-up, including wall injury and recurrent coarctation.

Balloon angioplasty for recurrent coarctation

As balloon angioplasty has fallen out of favour for native coarctation, it has gained popularity for recurrent coarctation. It is the preferred method at most centres for addressing this lesion and is supported by the American Heart Association consensus statement.[14] Patients who have undergone surgical arch reconstruction as part of a single-ventricle palliation are especially at risk for complications associated with recurrent coarctation. This complication can increase single-ventricular dysfunction and atrioventricular valve regurgitation. In a large study of 549 single-ventricle stage I arch reconstructions, 18% required re-intervention on the aortic arch, with good short-term results.[24] Success rates of angioplasty on recurrent coarctation are reported to be as high as 93%.[25] In the CCISC study, 80% of patients had a post-procedural systolic gradient <15 mmHg on upper- versus lower-extremity blood pressure testing.

Longer-term results for balloon dilation of recurrent coarctation are variable. Re-coarctation rates as high as 50% have been reported.[25,26] An overall 39% of patients in the single-ventricle study required another intervention after balloon dilation for recurrent coarctation.[24] Interestingly, in the CCISC study 94% of patients had a blood pressure gradient <15 mmHg at intermediate follow-up, suggesting further remodelling of the coarctation site in this subset of patients. The incidence of aortic wall injury is reported to be as low as 1% in this population. It is believed that scar tissue that develops from the initial surgical intervention helps protect this portion of the aorta during subsequent percutaneous interventions. In the CCISC cohort, only 17% of patients who had undergone balloon dilation of recurrent coarctation had signs of wall injury, compared with 43% of those who had undergone angioplasty of native coarctation. These data suggest that balloon dilation of recurrent coarctation is a safe option with acceptable results.

Coarctation stent placement

The principle of endovascular stents in the treatment of coarctation holds multiple theoretic advantages. There is an obvious advantage of radial strength that is thought to decrease recoil and therefore recurrent coarctation. There is no requirement for an intimal tear with a stent and hence, theoretically, the risk for aortic wall injury is lower. A large retrospective study published in 2007 examined 565 patients over the age of 4 years and showed acute success in 98% of them with a rate of aortic wall injury <4%.[27] The CCISC published their acute and long-term results in 2010 that were very similar to those of the retrospective study.[28] There was a 96% success rate defined as no significant blood pressure gradient or need for re-intervention. Wall injury was seen only in 1% of the population.

The Coarctation of the Aorta Stent Trial was started in 2007 as a prospective multi-centre trial to examine stent placement for coarctation.[1] In 2015, mid-term results were reported, which showed that 104 of 105 patients had undergone a successful implantation, with 100% success in those patients who had received the stent.[29] There were no acute adverse events. At 2-year follow-up the most

https://doi.org/10.1017/S1047951116001694 Published online by Cambridge University Press

common complication was stent fracture in 23 patients, although none resulted in loss of stent integrity or function. There were six patients with small aortic wall aneurysms at follow-up. In total, 19 patients required re-intervention for either treatment of wall injury (five patients) or for planned stent dilation. As per the study design, 60-month data will be published when available.

With the recognised risk for stent fracture and aortic wall injury, covered stents were studied as a rational option for those with previous stent-related complications, coarctation with aneurysm, or complex coarctation anatomy at higher risk for stent complications. Covered stents were recently approved by the Food and Drug Administration but have been widely available outside the United States of America for over a decade. In 2006, results were reported from 30 (14 native) international patients using the Cheatham-platinum covered stent (NuMED).[30] There was a mean decrease in coarctation gradient from 36 to 4 mmHg, and all patients who had undergone covered stent placement for aortic wall aneurysm had 100% exclusion. There were two acute stent fractures noted, one requiring a second covered stent. Follow-up data showed that four patients required re-intervention, all planned as a staged approach.

Earlier this year, mid-term results of the Coarctation of the Aorta Stent Trial II trial were published, and at around the same time the Cheatham-platinum covered stent was approved by the Food and Drug Administration.[31] In total, 158 patients across 19 centres received covered stent placement either for treatment of aortic wall injury in patients with coarctation (83 patients) or for prevention (75 patients) in those thought to be at high risk for wall injury associated with catheter-based treatment. There was both a statistically significant drop in pullback gradient immediately post implant and by blood pressure gradient at 30-day follow-up. Complete wall injury coverage was achieved in 92% of the treatment group. There were no new wall injury events reported.

Discussion

The long-standing debate on the best treatment modality for coarctation is not likely to end any time soon. One observational paper attempted to compare the results of coarctation repair between balloon angioplasty, stent placement (using the CCISC data), and surgery.[32] Although there was no difference in the rate of unplanned surgery at follow-up (mean of 1.7 years), those in the stent group had a higher rate of planned re-intervention. The balloon angioplasty group had a higher rate of aortic wall injury. In 2012, a Cochrane review was attempted to determine the most effective method between surgery and stent placement; however, no conclusions could be formed.[2]

As technologies and techniques improve, the answer to this question is most likely a moving target. We have already seen a significant decrease in the incidence of aortic wall injury associated with percutaneous treatment of coarctation, and as balloon/stent profiles continue to improve, access site complications will continue to decrease. As new technology becomes available, more studies are needed to specifically examine deployment techniques and their relation to results and adverse events. Although there will always be a role for surgery in the treatment of aortic arch anomalies, in the future we hope to provide less invasive, equally effective, and safer percutaneous approaches to a larger subset of patients requiring treatment for coarctation of the aorta.

References

1. Ringel RE, Gauvreau K, Moses H, Jenkins KJ. Coarctation of the Aorta Stent Trial (COAST): study design and rationale. Am Heart J 2012; 164: 7–13.
2. Pádua LM, Garcia LC, Rubira CJ, de Oliveira Carvalho PE. Stent placement versus surgery for coarctation of the thoracic aorta. Cochrane Database Syst Rev 2012; 5: CD008204.
3. Morgagni JB. Letter XVIII, art. 6. In: Morgagni JB, (ed.) The Seats and Causes of Diseases Investigated by Anatomy (Translated by B. Alexander) Millar, Cadell, Johnson and Payne, London, 1976: 462, pp.
4. Kvitting JP, Olin CL. Clarence Crafoord: a giant in cardiothoracic surgery, the first to repair aortic coarctation. Ann Thorac Surg 2009; 87: 342–346.
5. Singer M, Rowen M, Dorsey T. Transluminal aortic balloon angioplasty for coarctation of the aorta in the newborn. Am Heart J 1982; 103: 131–132.
6. Lock JE, Bass JL, Amplatz K, Fuhrman BP, Castaneda-Zuniga W. Balloon dilation angioplasty of aortic coarctations in infants and children. Circulation 1983; 68: 109–116.
7. O'Laughlin MP, Perry SB, Lock JE, Mullins CE. Use of endovascular stents in congenital heart disease. Circulation 1991; 83: 1923–1939.
8. Vossschulte K. Surgical correction of coarctation of the aorta by an "isthmusplastic" operation. Thorax 1961; 16: 338–345.
9. Waldhausen JA, Nahrwold DL. Repair of coarctation of the aorta with a subclavian flap. J Thorac Cardiovasc Surg 1966; 51: 532–533.
10. Gross RE. Treatment of certain aortic coarctations by homologous grafts; a report of nineteen cases. Ann Surg 1951; 134: 753–768.
11. Amato JJ, Rheinlander HF, Cleveland RJ. A method of enlarging the distal transverse arch in infants with hypoplasia and coarctation of the aorta. Ann Thorac Surg 1977; 23: 261–263.
12. Choudhry S, Balzer D, Murphy J, Nicolas R, Shahanavaz S. Percutaneous carotid artery access in infants 3 months of age. Catheter Cardiovasc Interv 2016; 87: 757–761.
13. Fischer DR, Ettedgui JA, Park SC, Siewers RD, Del Nido PJ. Carotid artery approach for balloon dilation of aortic valve stenosis in the neonate: a preliminary report. J Am Coll Cardiol 1990; 15: 1633–1636.
14. Feltes TF, Bacha E, Beekman RH, et al. Indications for cardiac catheterization and intervention in pediatric cardiac disease: a

https://doi.org/10.1017/S1047951116001694 Published online by Cambridge University Press

scientific statement from the American Heart Association. Circulation 2011; 123: 2607–2652.
15. De Vlieger G, Budts W, Dubois CL. Horner syndrome after stenting of a coarctation of the aorta. Heart 2010; 96: 714.
16. Daehnert I, Rotzsch C, Wiener M, Schneider P. Rapid right ventricular pacing is an alternative to adenosine in catheter interventional procedures for congenital heart disease. Heart 2004; 90: 1047–1050.
17. Marshall AC, Perry SB, Keane JF, et al. Early results and medium-term follow-up of stent implantation for mild residual or recurrent aortic coarctation. Am Heart J 2000; 139: 1054–1060.
18. Tynan M, Finley JP, Fontes V, Hess J, Kan J. Balloon angioplasty for the treatment of native coarctation: results of valvuloplasty and angioplasty of congenital anomalies registry. Am J Cardiol 1990; 65: 790–792.
19. Mendelsohn AM, Lloyd TR, Crowley DC, Sandhu SK, Kocis KC, Beekman RH. Late follow-up of balloon angioplasty in children with a native coarctation of the aorta. Am J Cardiol 1994; 74: 696–700.
20. Rao PS, Galal O, Smith PA, et al. Five- to nine-year follow-up results of balloon angioplasty of native aortic coarctation in infants and children. J Am Coll Cardiol 1996; 27: 462–470.
21. Fawzy ME, Fathala A, Osman A, et al. Twenty-two years of follow-up results of balloon angioplasty for discreet native coarctation of the aorta in adolescents and adults. Am Heart J 2008; 156: 910–917.
22. Harris KC, Du W, Cowley CG, Forbes TJ, Kim DW. A prospective observational multicenter study of balloon angioplasty for the treatment of native and recurrent coarctation of the aorta. Catheter Cardiovasc Interv 2014; 83: 1116–1123.
23. Cowley CG, Orsmond GS, Feola P, McQuillan L, Shaddy RE. Long-term, randomized comparison of balloon angioplasty and surgery for native coarctation of the aorta in childhood. Circulation 2005; 111: 3453–3456.
24. Ohye RG, Sleeper LA, Mahony L, et al. Comparison of shunt types in the Norwood procedure for single-ventricle lesions. N Engl J Med 2010; 362: 1980–1992.
25. Saxena A. Recurrent coarctation: interventional techniques and results. World J Pediatr Congenit Heart Surg 2015; 6: 257–265.
26. Yetman AT, Nykanen D, McCrindle BW, et al. Balloon angioplasty of recurrent coarctation: a 12-year review. J Am Coll Cardiol 1997; 30: 811–816.
27. Forbes TJ, Garekar S, Amin Z, et al. Procedural results and acute complications in stenting native and recurrent coarctation of the aorta in patients over 4 years of age: a multi-institutional study. Catheter Cardiovasc Interv 2007; 70: 276–285.
28. Holzer R, Qureshi S, Ghasemi A, et al. Stenting of aortic coarctation: acute, intermediate, and long-term results of a prospective multi-institutional registry – Congenital Cardiovascular Interventional Study Consortium (CCISC). Catheter Cardiovasc Interv 2010; 76: 553–563.
29. Meadows J, Minahan M, McElhinney DB, McEnaney K, Ringel R, on behalf of the COAST Investigators. Intermediate outcomes in the prospective, multicenter Coarctation of the Aorta Stent Trial (COAST). Circulation 2015; 131: 1656–1664.
30. Tzifa A, Ewert P, Brzezinska-Rajszys G. Covered Cheatham-platinum stents for aortic coarctation: early and intermediate-term results. J Am Coll Cardiol 2006; 47: 1457–1463.
31. Taggart NW., Minahan M, Cabalka AK., et al. Immediate Outcomes of Covered Stent Placement for Treatment or Prevention of Aortic Wall Injury Associated With Coarctation of the Aorta (COAST II). JACC Cardiovasc Interv 2016; 9: 484–493.
32. Forbes TJ, Kim DW, Du W, et al. Comparison of surgical, stent, and balloon angioplasty treatment of native coarctation of the aorta: an observational study by the CCISC (Congenital Cardiovascular Interventional Study Consortium). J Am Coll Cardiol 2011; 58: 2664–2674.