STATE-OF-THE-ART PAPER

Pediatric Cardiac Interventions

Ziyad M. Hijazi, MD, MPH, FACC, Sawsan M. Awad, MD

Chicago, Illinois

The field of pediatric cardiac interventions has witnessed a dramatic increase in the number and type of procedures performed. We review the most common procedures performed in the catheter laboratory. Lesions are divided according to their physiological characteristics into left-to-right shunting lesions (atrial septal defect, patent ductus arteriosus, ventricular septal defect), right-to-left shunting lesions (pulmonary stenosis, pulmonary atresia/intact ventricular septum), right heart obstructive lesions (peripheral arterial pulmonic stenosis, right ventricular outflow tract obstruction), and left heart obstructive lesions (aortic valve stenosis, coarctation of the aorta). In addition, a miscellaneous group of lesions is discussed. (J Am Coll Cardiol Intv 2008;1:603–11) © 2008 by the American College of Cardiology Foundation

In the past 2 to 3 decades, the field of pediatric interventional cardiology has experienced significant growth. Technological innovations have greatly advanced treatment of cardiovascular disease in both children and adults with congenital heart disease (CHD). Interventional therapy has become an acceptable alternative treatment for many CHD, including closure of atrial defects, muscular ventricular septal defects (VSDs), patent ductus arteriosus (PDA), dilation of stenotic valves (aortic and pulmonary), and dilation of stenotic vessels (branch pulmonary arteries, coarctation of the aorta [COA]). In some cases where the percutaneous approach is difficult or the patient still requires repair of other associated cardiac anomalies, a hybrid approach can be implemented with its obvious advantages to the patient.

In this article, we will review the advances and state-of-the-art in interventional therapy for CHD. For the best understanding of the various lesions that can be treated in the catheterization laboratory, we will attempt to divide the lesions based on their physiological characteristics.

From the Rush Center for Congenital and Structural Heart Disease and the Section of Cardiology, Department of Pediatrics, Rush University Medical Center, Chicago, Illinois.

Left-to-Right Shunting Lesions

Atrial level shunts, such as atrial septal defect (ASD) and patent foramen ovale, are common congenital cardiac defects. Because patent foramen ovale is quite common and there is still controversy about closure in patients who sustain a cryptogenic stroke, we elected not to discuss it in this article.

Atrial septal defects account for approximately 19% of all CHD (1). With the advances in diagnostic tools for CHD, the incidence of many of the defects has increased compared with reports from the past (2).

Patients with ASDs are usually asymptomatic in the first 2 decades of life. Usually, if the Q_p/Q_s ratio is more than 1.5:1, such patients may experience symptoms of shortness of breath and fatigue (3). As shunting continues, there are risks of development of right ventricular volume overload and later dysfunction, progressive pulmonary vascular disease, and atrial arrhythmias. In addition, these patients are at risk of development of paradoxical embolus (3–5). In 1974, King and Mills (6) performed the first successful transcatheter closure of a secundum ASD. After that, a number of different devices were developed with variable degrees of success (7–11). The currently approved devices by the U.S. Food and Drug Administration for clinical use are the Amplatzer septal occluder (ASO) (AGA Medical, Plymouth, Minnesota),

and the Helex septal occluder (W. L. Gore and Associates, Flagstaff, Arizona).

The ASO provides good closure rates (97%) with similar or lower complication rates than open-heart surgery (12,13).

The Helex septal occluder consists of an expanded polytetrafluoroethylene patch material with hydrophilic coating, supported by a nickel-titanium (nitinol) superelastic wire frame in the shape of a coil. This device is not suitable for defects larger than 18 mm (14).

Various modifications of the ASO have been reported, including fenestrated ASO and the cribriform ASO for multifenestrated ASDs or ASDs with septal aneurysms (15,16). We prefer the use of intracardiac echocardiography to guide closure of ASD, even in smaller children (17). Figure 1 demonstrates steps of closure of a large ASD using ASO under intracardiac echocardiography guidance.

Ventricular septal defects are considered the most common cardiac abnormalities found in children, accounting for approximately 30% of all defects (1,18). Ventricular septal defects could be classified into 4 major categories according to Soto et al. (19) with the perimembranous category being the most common representing type followed by the muscular defects. A VSD can rarely be iatrogenic secondary to traumatic injury to the chest and in 0.2% of patients following ventricular septal rupture associated with myocardial infarction. Large VSDs are unlikely to close spontaneously, and patients with such defects will present with signs and symptoms of congestive heart failure and failure to thrive. All VSDs can be repaired surgically with the exception of the apical defects and Swiss cheese–type of VSD. The latter consists of multiple apical muscular VSDs due perhaps to excessive resorption of myocardial tissue during formation of the muscular part of the interventricular septum. The overall risk for VSD repair is less than 5%. Mortality and morbidity rates increase with multiple VSDs, pulmonary hypertension, residual VSD, and complex associated anomalies. Complete heart block immediately after surgery occurs in less than 1% of patients. Late-onset complete heart block is occasionally a problem, especially in patients who have a post-operative complete right bundle branch block with a left anterior hemiblock (20,21).

Since the first successful percutaneous VSD device closure in 1987 by Lock et al. (22), there have been several reports of transcatheter closure of the VSD using different devices (23–28). The Amplatzer muscular occluder device (AGA Medical) was specifically designed for the ventricular septum. It is made of 0.004- to 0.005-inch nitinol wire. Holzer et al. (29) reported on the use of this device in a U.S. registry. Their data were prospectively collected from 83 procedures involving 75 patients who underwent an attempt of percutaneous and/or perventricular device closure of hemodynamically significant muscular VSDs. The device was implanted successfully in 86.7% procedures. Complete closure was achieved in 47.2% at 24 h, which increased to 69.6% at 6 months and to 92.3% at 12 months follow-up. Figure 2 shows a patient's muscular VSD after closure with a device.

In smaller patients (less than 5 kg) and patients with abnormal septal planes (e.g., double outlet right ventricle, transposition of the great vessels) or patients with other associated cardiac defects requiring repair, the hybrid approach has been advocated as an alternative to conventional surgery on cardiopulmonary bypass (30).

Percutaneous transcatheter closure of perimembranous VSDs using the Amplatzer membranous VSD occluder (AGA Medical) has recently become available as well. This device has a unique design with a left ventricular desk that is asymmetric (31). However, the complication rate using this device is more than that of the surgical closure, especially the incidence of complete heart block (32,33). Due to the high incidence of complete heart block, clinical trials in the U.S. using this device have been terminated.

Patent ductus arteriosus is the presence of the normal fetal structure commonly connecting between the left pulmonary artery and the descending aorta beyond 2 to 3 weeks of life and represents 5% to 10% of all CHD, excluding those in premature infants (34).

In infants beyond the neonatal period, device and or coil closure has been advocated since the 1980s (4).

The Amplatzer duct occluder (ADO) is currently the most commonly used device with a low rate of procedure- or device-related complications (35). Figure 3 demonstrates closure in a child with PDA.

Modifications of the ADO device have taken place to overcome certain technical difficulties. The angled ADO was developed to overcome the protrusion of the original device in the aortic lumen of smaller children causing partial aortic obstruction (36,37). However, the manufacturer never pursued this device. Another modification to the original device is the ADO-II (AGA Medical), which has a cylindrical waist with retention disks on either end to secure it in the PDA. This device is currently under clinical trials in the U.S.

The Nit-Occlud PDA system (Pfm Medical, Oceanside, California) was used by Celiker et al. (38) in 2005 to close moderate-size PDA.

Coronary arteriovenous fistulae can originate from all major epicardial coronary arteries, and drainage usually occurs to the coronary sinus, right atrium, right ventricle, or pulmonary artery. These collaterals can become markedly

Abbreviations and Acronyms

ADO = Amplatzer duct occluder

AS = aortic valve stenosis

ASD = atrial septal defect

ASO = Amplatzer septal occluder

CHD = congenital heart disease

COA = coarctation of the aorta

PDA = patent ductus arteriosus

PS = pulmonary stenosis

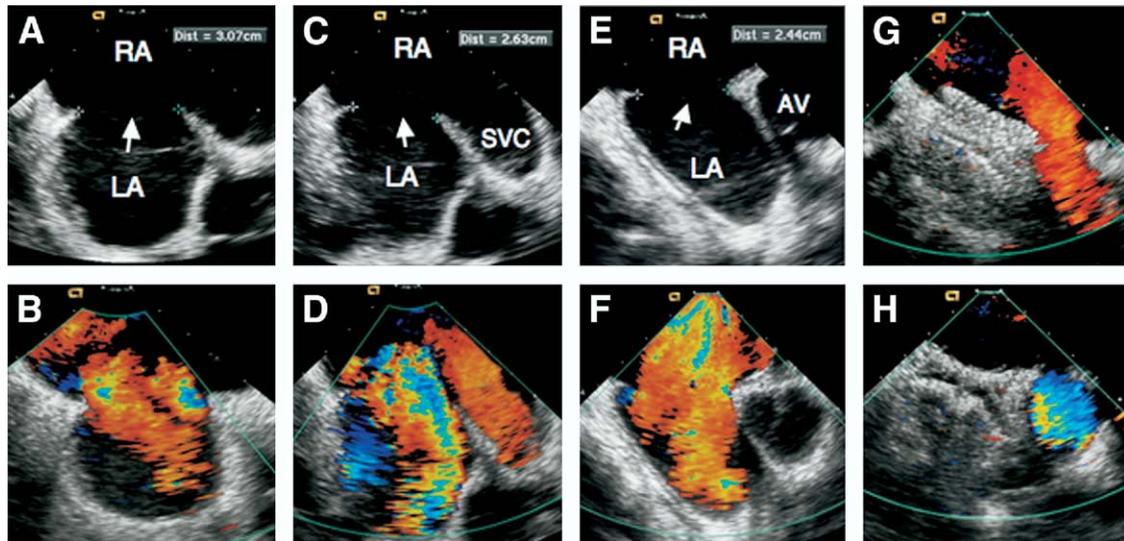**VSD** = ventricular septal defect

Figure 1. Intracardiac Echocardiographic Images During Transcatheter Closure of a Large Secundum ASD in a 12.5-Year-Old Male Child

(A, B) Images in septal view without **(A)** and with **(B)** color Doppler, demonstrating the presence of a large defect **(arrow)** measuring 31 mm. **(C, D)** Images in long axis (caval) view without **(C)** and with **(D)** color Doppler, demonstrating the large defect **(arrow)** measuring 26 mm. **(E, F)** Images in short-axis view without **(E)** and with **(F)** color Doppler, demonstrating the large defect **(arrow)** measuring 24 mm. **(G, H)** Images after a 34-mm device was implanted in caval **(G)** and short-axis **(H)** view, demonstrating good device position and no residual shunt. ASD = atrial septal defect; AV = aortic valve; LA = left atrium; RA = right atrium; SVC = superior vena cava.

enlarged and can lead to significant left-to-right shunting with right-sided volume overload and effective coronary arterial steal leading to ischemia (3). Coils and devices have been used to close clinically significant fistulae. The ASD closure devices and the ADO have been used successfully.

Complications associated with catheter closure of such fistulae include transient ischemic episodes, device embolization to various chambers/vessels, myocardial infarction, and transient atrial arrhythmias (39,40).

Aortopulmonary windows are rare forms of CHD (41). Large defects are usually closed surgically. If the defect is small, percutaneous device closure may be feasible (42,43).

Right-to-Left Shunting Lesions

Isolated valvular pulmonary stenosis (PS) represents 80% to 90% of all patients with right ventricular outflow tract obstruction, and 8% to 10% of all patients with CHD. The
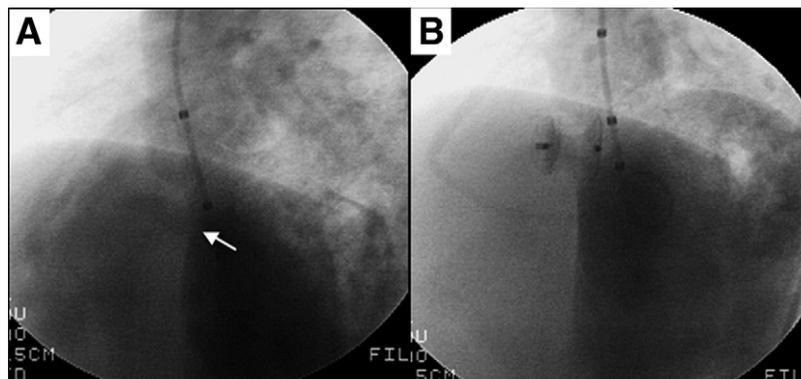

Figure 2. Cine Fluoroscopic Images in a 6-Year-Old Female Child With High Muscular VSD

(A) Angiogram in the left ventricle in the long axial oblique view (long axial oblique: 50°, cranial: 15°) showing a high muscular ventricular septal defect (VSD) **(arrow)** that measured about 6 mm. **(B)** Repeat left ventricle angiogram after deployment of a 8-mm Amplatzer muscular VSD occluder showing complete closure and good device position.
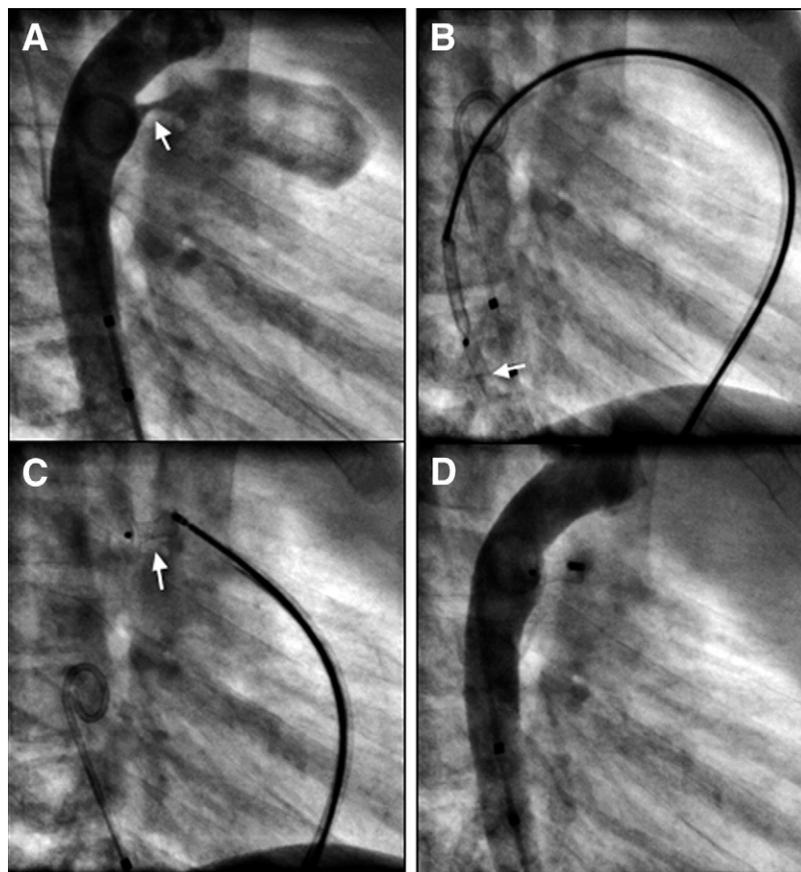
Figure 3. Cine Fluoroscopic Images in the Lateral Projection in a 6.5-Year-Old Female Child With a PDA

(A) Angiogram in the descending aorta demonstrating a 2-mm patent ductus arteriosus (PDA) at its narrowest diameter (arrow), angiographic type A. (B) 6-F delivery sheath across the PDA into the descending aorta with the device near the tip of the sheath (arrow). (C) Deployment of the retention desk and tubular part of a 6- to 4-mm Amplatzer duct occluder (arrow). (D) Final angiogram after the device has been released, demonstrating complete closure of the ductus.

stenotic valve is usually dome-shaped, with diffuse thickening and commissural fusion.

With systemic and suprasystemic right ventricular pressure, right-to-left shunt occurs at the atrial level, and this may lead to cyanosis. Patients with mild PS are usually asymptomatic. Indications for treatment include symptomatic patients, asymptomatic patients with severe PS (gradient >80 mm Hg), or evidence of right ventricular hypertrophy. Balloon pulmonary valvuloplasty was initially described in children by Kan et al. (44). The success rates are excellent for children with classical PS; however, for patients with dysplastic valves or with supravalvular and or subvalvular PS, the success rate is low (7).

In selected infants with membranous pulmonary atresia and adequately sized right ventricle, perforation of the membrane with either the stiff end of a wire or using radiofrequency perforation followed by balloon dilation has been successful in creating an open right ventricular outflow tract. The radiofrequency technique is promising, but it has

the risk of inadvertent perforation of the right ventricular outflow tract (45,46).

In cases of pulmonary atresia with intact ventricular septum, right-to-left shunt occurs at the atrial level. After construction of the right ventricular outflow tract in such lesions, device closure of the atrial communication may be advised. In these cases, temporary test occlusion of the atrial communication with a balloon may be necessary before device closure depending on the hemodynamic response. If the right atrial pressure does not increase significantly from baseline (no more than 5-mm Hg mean increase) with stable blood pressure, then device closure of the defect can be carried out using a device at least 2 to 4 mm larger than the "balloon stretched diameter" of the defect.

Right-to-left shunt across the atrial level communication is found in certain lesions. In some forms of complex CHD, the presence of unrestrictive atrial communication is crucial for survival of patients with such defects until palliative and/or corrective surgeries take place. Right-to-left shunt-

ing across the atrial septum is essential in certain congenital heart defects. An example of this is in patients with tricuspid and/or pulmonary atresia with intact ventricular septum. Patients with hypoplastic left heart syndrome require decompression of their hypertensive left atrium if the septum is intact or restrictive. Post-operative Fontan patients with low cardiac output may require a fenestration in the Fontan circuit to allow right-to-left shunting. Further, some patients may require mixing at the atrial level to enhance their systemic saturation (patients with d-transposition). There are multiple techniques to create an atrial septal defect and/or dilate a restrictive, already present, defect. In 1966, Rashkind and Miller (47) first described balloon atrial septostomy as palliation for patients with transposition of the great arteries to improve saturation. In 1996, Coe et al. (48) first reported the use of cutting balloons to create an atrial communication in piglets. The technique proved to be effective in creating adequately sized atrial septal communication. Later, this technique was used to create atrial communication after septal perforation or radiofrequency septal perforation in cases of thickened intact atrial septum (49). Park et al. (50) first described blade atrial septostomy. This procedure is recommended for older patients (6 to 8 weeks) where the presence of an adequate atrial septal communication is crucial to patient survival.

Atrial communication may be needed for short- or long-term palliation. Patients with pulmonary hypertension or a failed Fontan procedure will require the communication on a long-term basis. In such cases, stenting of the defect may afford long-term palliation (51).

Left-Sided Obstructive Lesions

Valvular aortic valve stenosis (AS) occurs in approximately 3% to 6% of patients with CHD (1,52). The stenotic valve is usually secondary to increased thickening and rigidity of the valve tissue and variable degrees of commissural fusion. As stenosis progresses, hypertrophy increases. With severe hypertrophy and valvular obstruction, myocardial ischemia may result from the combination of limited cardiac output, reduced coronary perfusion, and increased myocardial oxygen consumption.

In neonatal critical AS (left ventricular outflow tract obstruction at valvular level, which presents in the first few days of life and is a duct-dependent lesion), congestive heart failure and shock occurs around the time of natural PDA closure. In older children, the presentation could be the systolic ejection murmur characteristic for valvular AS.

Indications for intervention include neonates with critical AS irrespective of the gradient and infants and children with peak-to-peak gradient across the valve of more than 55 mm Hg (53). Aortic valvuloplasty for congenital AS is a safe technique with a reported incidence of complications of 3%

(54,55). The initial balloon chosen for the valvuloplasty should be 85% to 90% of the aortic valve annulus measured via aortic angiography. Optimal results from the procedure should achieve 50% or more reduction in the gradient with no increase in aortic regurgitation. If a nonsatisfactory result is encountered and no significant increase in aortic regurgitation is noticed, a larger balloon diameter can be used to repeat the procedure.

Coarctation of the aorta accounts for 5% to 8% of all CHD (1). It is more common in males than females. There is a high incidence, 15% to 20%, of COA in patients with Turner syndrome. Surgery had been the standard therapy for COA until Sos et al. (56) in 1979 showed that excised segments of coarcted aorta could be dilated. After that, the technique was used and modified, and the results were reported (57–59). Indications for balloon dilation of COA are basically the same as those for surgery, which include hypertension proximal to the coarctation with a resting systolic pressure gradient across the narrowed segment >20 mm Hg or angiographically severe coarctation with extensive collaterals (53). There is controversy about balloon dilation of native COA due to the risk of aneurysm formation after angioplasty. Some believe that angioplasty should only be performed on cases of recoarctation; others advocate its use in both native and recurrent coarctation (60). The use of lower profile sheaths and balloons leads to marked improvement in the angioplasty results. Some patients who had their COA repaired surgically early in life develop recurrent or residual COA (61,62). Balloon angioplasty is a preferable alternative to surgery for treatment of recoarctation of the aorta with good acute results and low complication rates (63). Endovascular stent implantation has become an accepted modality for treatment of native and recurrent coarctation of the aorta in children and adults (64–66). In recent years, balloon-expandable stents mounted on a balloon dilation catheter serve as endovascular prostheses that maintain patency of the stenotic vessels and vascular channels. The Palmaz balloon-expandable stents (Johnson & Johnson, Warren, New Jersey) are the most commonly used in the pediatric age group. Figure 4 shows a child's COA that was successfully treated with a stent placement.

The most common abnormalities/complications usually encountered following intravascular stent placement are the development of an aneurysm and intimal proliferation within the stent (64,67–70). Although covered stents are useful in the management of certain patients with coarctation, aneurysm formation may still occur in patients with aortic wall weakness (71).

Congenital mitral valve stenosis is a rare lesion. Balloon angioplasty is a well-known treatment modality for treatment of rheumatic mitral valve stenosis (72). However, the application of this technique in cases of congenital mitral valve stenosis is limited with a low success rate.
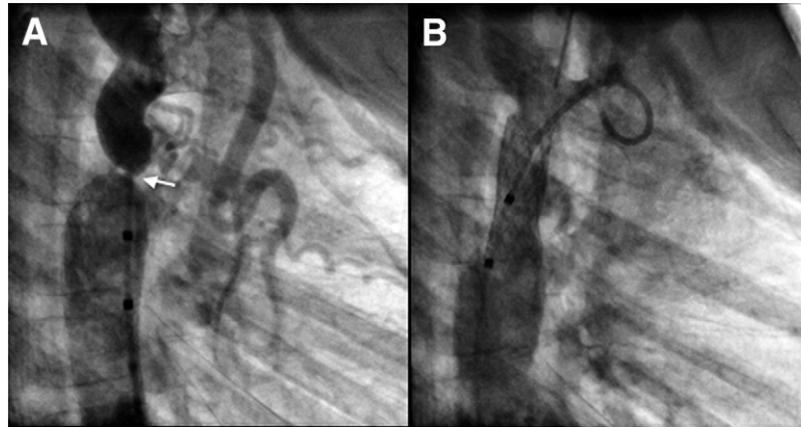
Figure 4. Cine Fluoroscopic Images in the Lateral Projection in a 6-Year-Old Male Child With Severe COA With a Gradient of 31 mm Hg

(A) Angiogram in the aortic arch demonstrating the presence of tight coarctation of the aorta (COA) **(arrow)**. The narrowest diameter measures 2.5 mm.
(B) Repeat angiogram in the arch after deployment of a P2510 Genesis stent mounted initially over a 9 mm × 2 cm Z-MED balloon (NuMED Inc., Hopkinton, New York) then further dilated with a 12 mm × 2.5 cm Tyshak balloon. This angiogram demonstrates good stent position with a final diameter of 9 mm and the final gradient was 4 mm Hg.

Right-Sided Obstructive Lesions

The overall frequency of peripheral arterial pulmonic stenosis is 2% to 3% of all CHD. It either is an isolated lesion or associated with other cardiac defects, such as VSD, tetralogy of Fallot, PDA, and ASD. The lesion is common in certain syndromes, such as rubella, Williams, Noonan, Alagille, Ehlers-Danlos, cutis laxa, LEOPARD, and Silver-Russell syndromes (73–75).

Patients with mild to moderate arterial obstruction are usually asymptomatic. Cases with severe stenosis may have dyspnea on exertion, easy fatigability, and occasional right-sided heart failure. Treatment of pulmonary artery stenosis depends on the site of the stenotic segment. Percutaneous pulmonary angioplasty is suitable for distal lesions unreachable by surgery, and surgical pulmonary arterioplasty is feasible for more proximal lesions.

Variable modalities of percutaneous treatment regimens include balloon pulmonary angioplasty, cutting balloons, and intravascular stent placement.

Balloon pulmonary angioplasty was first described by Martin et al. (76) to treat peripheral pulmonary stenosis in a post-operative 18-year-old after repair of pulmonary atresia with VSD. Despite advances in balloon types and pressure achieved, around one-third of vessels, more often distal, remain resistant to angioplasty (77).

The use of cutting balloons is an effective treatment for small lobar pulmonary artery stenosis refractory to currently available techniques (78).

Stenting of branch pulmonary arteries is frequently used in children with pulmonary artery stenosis and/or hypoplasia (79–81). Due to the higher immediate success and lower incidence of restenosis, stenting of pulmonary arteries may be a reasonable first-line therapy.

Intraoperative intravascular stent placement is a hybrid technique that could be used in difficult situations. It is suitable in early post-operative period, difficult vascular anatomy, bilateral stenoses requiring simultaneous stent implantation, short proximal segment stenosis (too short for the shortest stent available), marginal hemodynamics, severe bilateral branch stenosis, patients on extracorporeal membrane oxygenation, and patients with other cardiac lesions requiring surgery (82).

Miscellaneous Lesions Requiring Percutaneous Intervention

Patients after Fontan operation. Often a fenestration is created between the inferior vena caval pathway and the body of the right atrium to allow decompression to the systemic circuit. In the longer term, there may be a significant right-to-left shunt through such fenestrations, causing systemic hypoxemia and desaturation. Further, such fenestration may predispose the patient to a paradoxical embolism. These fenestrations are often amenable to closure in the cardiac catheter laboratory, using the same type of devices that would be used to close an ASD (83).

Aortopulmonary collaterals. Collateral vessels occur in a wide variety of conditions, including pulmonary atresia with VSD, tetralogy of Fallot, scimitar syndrome, and in hearts undergoing Fontan-type reconstruction. They may be arterial or venous and may shunt left to right or right to left. As they are often difficult for the surgeon to access, they may be

occluded with coils or occluder devices in the cardiac catheter laboratory (84).

For an aortopulmonary collateral vessel to be occluded, it must supply a segment of the pulmonary arterial tree that receives dual arterial supply and must not be required for adequate systemic arterial oxygen content.

Conduit obstruction. Extracardiac conduits may be used to connect the subpulmonary ventricle to the pulmonary arteries in patients with complex congenital disease. These conduits can develop obstruction secondary to severe angulation, calcification, sternal compression, or tissue proliferation, mainly at anastomotic sites. Restenosis is common after balloon angioplasty procedures. Stent implantation has demonstrated better long-term outcome, yet with recognized risks (85). Risks include stent fracture, limitation of the ability of future surgical conduit replacement, severe regurgitation in valved conduits, and coronary artery compression.

After tetralogy of Fallot repair. Tetralogy of Fallot accounts for 3.5% of infants born with CHD. Pulmonary regurgitation, residual peripheral arterial pulmonic stenosis, and small residual VSDs are common after surgical repair of tetralogy of Fallot.

The use of balloon angioplasty and the cutting balloon has been successful in releasing residual peripheral arterial pulmonic stenoses that are usually more distal than the surgeons can reach. Percutaneous intravascular stent placement has been very successful and avoids restenosis that occurs due to the elastic recoil of the arteries. In situations where a significant residual defect is noticed, percutaneous device closure may take place if feasible technically.

Pulmonary regurgitation is common following repair of tetralogy of Fallot. Although well tolerated for some years, formal exercise testing shows a negative correlation between pulmonary regurgitant fraction measured angiographically and exercise ability (86). The effects of pulmonary regurgitation include atrial arrhythmias, heart failure, prolonged QRS interval duration, increased risk of malignant ventricular arrhythmias, and increased risk of sudden death.

Surgery was the only available option for treatment of post-operative pulmonary regurgitation until Bonhoeffer et al. (87) reported the first successful animal experience with percutaneous pulmonary valve implantation. Many successful reports of percutaneous pulmonary valve replacement followed then with encouraging results. Unresolved issues remain, including valve durability, stent fracture, device embolization, adjacent structure impingement, limited valve size, recurrent regurgitation and stenosis, and the need for large catheters for delivery (88). Modifications of current technique of percutaneous pulmonary valve placement have been suggested to allow using the percutaneous valves in right ventricular outflow tracts larger than 22 mm. The suggested hybrid approach includes banding the main pulmonary artery surgically to 18 mm then placement of the

stent-mounted bovine jugular venous valve by either an "off-pump" transventricular approach or a percutaneous approach (89,90). Right ventricular outflow tract reducers are being developed so that percutaneous valve implantation will be possible (91).

Summary

Percutaneous intervention in pediatric cardiac disease had developed in the past 3 decades. There are devices approved for percutaneous closure of ASDs, PDAs, and muscular VSDs. The era of percutaneous valve implantation is just beginning, and we suspect the next few years will witness the development of miniaturized valve delivery systems to enable implantation in smaller children.

Performing interventional cardiac catheterization in children requires high skills and training. Only trained pediatric/congenital cardiologists with expertise in interventional therapy should perform such complex procedures. Fully equipped catheterization laboratory, surgical backup, and extracorporeal membrane oxygenation support capabilities should be available in any center planning to perform interventional cardiac catheterization.

Reprint requests and correspondence: Dr. Ziyad M. Hijazi, Rush Center for Congenital & Structural Heart Disease, 1653 West Congress Parkway, Jones 770, Chicago, Illinois 60637. E-mail: zhijazi@rush.edu.

REFERENCES

1. Miyague NI, Cardoso SM, Meyer F, et al. Epidemiological study of congenital heart defects in children and adolescents. Analysis of 4,538 cases. Arq Bras Cardiol 2003;80:269–78.
2. Carlgren LE. The incidence of congenital heart disease in children born in Gothenburg 1941–1950. Br Heart J 1959;21:40–50.
3. Inglessis I, Landzberg MJ. Interventional catheterization in adult congenital heart disease. Circulation 2007;115:1622–33.
4. Andrews RE, Tulloh RM. Interventional cardiac catheterization in congenital heart disease. Arch Dis Child 2004;89:1168–73.
5. Mullen MJ, Hildick-Smith D, De Giovanni JV, et al. BioSTAR Evaluation STudy (BEST): a prospective, multicenter, phase I clinical trial to evaluate the feasibility, efficacy, and safety of the BioSTAR bioabsorbable septal repair implant for the closure of atrial-level shunts. Circulation 2006;114:1962–7.
6. King TD, Mills NL. Nonoperative closure of atrial septal defects. Surgery 1974;75:383–8.
7. Vincent RN, Diehl HJ. Interventions in pediatric cardiac catheterization. Crit Care Nurs Q 2002;25:37–47.
8. Rashkind WJ. Interventional cardiac catheterization in congenital heart disease. Cardiovasc Clin 1985;15:303–16.
9. Lock JE, Rome JJ, Davis R, et al. Transcatheter closure of atrial septal defects. Experimental studies. Circulation 1989;79:1091–9.
10. Hausdorf G, Schneider M, Franzbach B, Kampmann C, Kargus K, Goeldner B. Transcatheter closure of secundum atrial septal defects with the atrial septal defect occlusion system (ASDOS): initial experience in children. Heart 1996;75:83–8.
11. Rickers C, Hamm C, Stern H, et al. Percutaneous closure of atrial septal defect with a new self-centering device ("angel wings"). Heart 1998;80:517–21.

12. Du ZD, Hijazi ZM, Kleinman CS, Silverman NH, Larntz K. Comparison between transcatheter and surgical closure of secundum atrial septal defect in children and adults: results of a multicenter non-randomized trial. J Am Coll Cardiol 2002;39:1836–44.

13. Diab KA, Cao QL, Bacha EA, Hijazi ZM. Device closure of atrial septal defects with the Amplatzer septal occluder: safety and outcome in infants. J Thorac Cardiovasc Surg 2007;134:960–6.

14. Jones TK, Latson LA, Zahn E, et al., on behalf of Multicenter Pivotal Study of the HELEX Septal Occluder Investigators. Results of the U.S. multicenter pivotal study of the HELEX septal occluder for percutaneous closure of secundum atrial septal defects. J Am Coll Cardiol 2007;49:2215–21.

15. Amin Z, Danford DA, Pedra CA. A new Amplatzer device to maintain patency of Fontan fenestrations and atrial septal defects. Catheter Cardiovasc Interv 2002;57:246–51.

16. Cheatham JP, Hill SL, Chisolm JL. Initial results using the new cribriform Amplatzer septal occluder for transcatheter closure of multifenestrated atrial septal defects with septal aneurysm. Catheter Cardiovasc Interv 2003;60:126.

17. Patel A, Cao QL, Koenig PR, Hijazi ZM. Intracardiac echocardiography to guide closure of atrial septal defects in children less than 15 kilograms. Catheter Cardiovasc Interv 2006;68:287–91.

18. Lewis DA, Loffredo CA, Corre-Villasenor A, Wilson PD, Martin GR. Descriptive epidemiology of membranous and muscular ventricular septal defects in the Baltimore-Washington Infant Study. Cardiol Young 1996;6:281–90.

19. Soto B, Becker AE, Moulaert AJ, Lie JT, Anderson RH. Classification of ventricular septal defects. Br Heart J 1980;43:332–43.

20. Serraf A, Lacour-Gayet F, Bruniaux J, et al. Surgical management of isolated multiple ventricular septal defects. Logical approach in 130 cases. J Thorac Cardiovasc Surg 1992;103:437–43.

21. Kitagawa T, Durham LA, Mosca RS, Bove EL. Techniques and results in the management of multiple ventricular septal defects. J Thorac Cardiovasc Surg 1998;115:848–56.

22. Lock JE, Block PC, McKay RG, Baim DS, Keane JF. Transcatheter closure of ventricular septal defects. Circulation 1988;78:361–8.

23. Rigby ML, Redington AN. Primary transcatheter umbrella closure of perimembranous ventricular septal defect. Br Heart J 1995;73:585–6.

24. Sideris EB, Walsh KP, Haddad JL, Chen CR, Ren SG, Kulkarni H. Occlusion of congenital ventricular septal defects by the buttoned device. "Buttoned device" Clinical Trials International Register. Heart 1997;77:276–9.

25. Thanopoulos BD, Tsaousis GS, Konstadopoulou GN, Zarayelyan AG. Transcatheter closure of muscular ventricular septal defects with the Amplatzer Ventricular Septal Defect Occluder: initial clinical applications in children. J Am Coll Cardiol 1999;33:1395–9.

26. Kalra GS, Verma PK, Dhall A, Singh S, Arora R. Transcatheter device closure of ventricular septal defects: immediate results and intermediate-term follow-up. Am Heart J 1999;138:339–44.

27. Hijazi ZM, Hakim F, Al-Fadley F, Abdelhamid J, Cao QL. Transcatheter closure of single muscular ventricular septal defects using the Amplatzer Muscular VSD Occluder: initial results and technical considerations. Catheter Cardiovasc Interv 2000;49:167–72.

28. Knauth AL, Lock JE, Perry SB, et al. Transcatheter device closure of congenital and postoperative residual ventricular septal defects. Circulation 2004;110:501–7.

29. Holzer R, Balzer D, Cao QL, Lock K, Hijazi ZM. Device closure of muscular ventricular septal defects using the Amplatzer muscular ventricular septal defect occluder: immediate and mid-term results of a U.S. registry. J Am Coll Cardiol 2004;43:1257–63.

30. Bacha EA, Cao QL, Galantowicz ME, et al. Multicenter experience with perventricular device closure of muscular ventricular septal defects. Pediatr Cardiol 2005;26:169–75.

31. Hijazi ZM, Hakim F, Haweleh AA, et al. Catheter closure of perimembranous ventricular septal defects using the Amplatzer membranous VSD occluder: initial clinical experience. Catheter Cardiovasc Interv 2002;56:508–15.

32. Fu YC, Bass J, Amin Z, et al. Transcatheter closure of perimembranous ventricular septal defects using the new Amplatzer Membranous VSD occluder. J Am Coll Cardiol 2006;47:319–25.

33. Holzer R, De Giovanni J, Walsh KP, et al. Transcatheter closure of perimembranous ventricular septal defects using the Amplatzer Membranous VSD occluder: immediate and mid-term results of an international registry. Catheter Cardiovasc Interv 2006;68:620–8.

34. Moore P, Brook MM, Heymann MA. Patent ductus arteriosus. In: Allen HD, Gutgesell HP, Clark EB, and Driscoll DJ, editors. Moss and Adams' Heart Disease in Infants, Children, and Adolescents. Philadelphia, PA: Lippincott, Williams & Wilkins, 2001:652–69.

35. Pass RH, Hijazi ZM, Hsu DT, Lewis V, Hellenbrand WE. Multicenter USA Amplatzer patent ductus arteriosus occlusion device trial: initial and one-year results. J Am Coll Cardiol 2004;44:513–9.

36. Vijayalakshmi IB, Chitra N, Rajasri R, Vasudevan K. Initial clinical experience in transcatheter closure of large patent arterial ducts in infants using the modified and angled Amplatzer duct occluder. Cardiol Young 2006;16:378–84.

37. Masura J, Gavora P, Podnar T. Transcatheter occlusion of patent ductus arteriosus using a new angled Amplatzer duct occluder: initial clinical experience. Catheter Cardiovasc Interv 2003;58:261–7.

38. Celiker A, Aypar E, Karagöz T, Dilber E, Ceviz N. Transcatheter closure of patent ductus arteriosus with Nit-Occlud coils. Catheter Cardiovasc Interv 2005;65:569–76.

39. Armsby LR, Keane JF, Sherwood MC, Forbess JM, Perry SB, Lock JE. Management of coronary artery fistulae: patient selection and results of transcatheter closure. J Am Coll Cardiol 2002;39:1026–32.

40. Behera SK, Danon S, Levi DS, Moore JW. Transcatheter closure of coronary artery fistulae using the Amplatzer Duct Occluder. Catheter Cardiovasc Interv 2006;68:242–8.

41. Luisi SV, Ashraf MH, Gula G, Radley-Smith R, Yacoub M. Anomalous origin of the right coronary artery with aortopulmonary window: functional and surgical considerations. Thorax 1980;35:446–52.

42. Stamato T, Benson, LN, Smallhorn JF, Freedom RM. Transcatheter closure of an aorto-pulmonary window with a modified double umbrella occluder system. Cathet Cardiovasc Diagn 1995;35:165–7.

43. Tulloh RM, Rigby ML. Transcatheter umbrella closure of aorto-pulmonary window. Heart 1997;77:479–80.

44. Kan JS, White RI Jr., Mitchell SE, Anderson JH, Gardner TJ. Percutaneous transluminal balloon valvuloplasty for pulmonary valve stenosis. Circulation 1984;69:554–60.

45. Hausdorf G, Schneider M, Lange P. Catheter creation of an open outflow tract in previously atretic right ventricular outflow tract associated with ventricular septal defect. Am J Cardiol 1993;72:354–6.

46. Hijazi ZM, Patel H, Cao QL, Warner K. Transcatheter retrograde radio-frequency perforation of the pulmonic valve in pulmonary atresia with intact ventricular septum, using a 2 French catheter. Cathet Cardiovasc Diagn 1998;45:151–4.

47. Rashkind WJ, Miller W. Creation of an atrial septal defect without thoracotomy: a palliative approach to complete transposition of the great arteries. JAMA 1966;196:991–2.

48. Coe JY, Chen RP, Timinsky J, Robertson MA, Dyck J. A novel method to create atrial septal defect using a cutting balloon in piglets. Am J Cardiol 1996;78:1323–6.

49. Hill SL, Mizelle KM, Vellucci SM, Feltes TF, Cheatham JP. Radiofrequency perforation and cutting balloon septoplasty of intact atrial septum in a newborn with hypoplastic left heart syndrome using transesophageal ICE probe guidance. Catheter Cardiovasc Interv 2005;64:214–7.

50. Park SC, Zuberbuhler JR, Neches WH, Lennox CC, Zoltun RA. A new atrial septostomy technique. Cathet Cardiovasc Diagn 1975;1:195–201.

51. Bacha EA, Hijazi ZM. Hybrid procedures in pediatric cardiac surgery. Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu 2005;8:78–85.

52. Roberts WC. Anatomically isolated aortic valvular disease. The case against its being of rheumatic etiology. Am J Med 1970;49:151–9.

53. Allen HD, Beekman RH III, Garson A Jr., et al. Pediatric therapeutic cardiac catheterization: a statement for healthcare professionals from the Council on Cardiovascular Disease in the Young. American Heart Association. Circulation 1998;97:609–25.

54. Moore P, Egito E, Mowrey H, Perry SB, Lock JE, Keane JF. Midterm results of balloon dilation of congenital aortic stenosis: predictors of success. J Am Coll Cardiol 1996;27:1257–63.

55. Pedra CA, Sidhu R, McCrindle BW, et al. Outcomes after balloon dilation of congenital aortic stenosis in children and adolescents. Cardiol Young 2004;14:315–21.

56. Sos T, Sniderman KW, Rettek-Sos B, Strupp A, Alonso DR. Percutaneous transluminal dilatation of coarctation of thoracic aorta post mortem. Lancet 1979;2:970–1.

57. Lock JE, Bass JL, Amplatz K, Fuhrman BP, Casteneda-Zuniga W. Balloon dilation angioplasty of aortic coarctations in infants and children. Circulation 1983;68:109–16.

58. Kan JS, White RI Jr., Mitchell SE, Farmlett EJ, Donahoo JS, Gardner TJ. Treatment of restenosis of coarctation by percutaneous transluminal angioplasty. Circulation 1983;68:1087–94.

59. Lababidi ZA, Daskalopoulos DA, Stoeckle H Jr. Transluminal balloon coarctation angioplasty: experience with 27 patients. Am J Cardiol 1984;54:1288–91.

60. Allen HD, Marx GR, Ovitt TW, Goldberg SJ. Balloon dilation angioplasty for coarctation of the aorta. Am J Cardiol 1986;57:828–32.

61. Kopf GS, Hellenbrand W, Kleinman C, Lister G, Talner N, Laks H. Repair of aortic coarctation in the first three months of life: immediate and long-term results. Ann Thorac Surg 1986;41:425–30.

62. Cobanoglu A, Teply JF, Grunkemeier GL, Sunderland CO, Starr A. Coarctation of the aorta in patients younger than three months: a critique of the subclavian flap operation. J Thorac Cardiovasc Surg 1985;89:128–35.

63. Hellenbrand WE, Allen HD, Golinko RJ, Hagler DJ, Lutin W, Kan J. Balloon angioplasty for aortic recoarctation: results of Valvuloplasty and Angioplasty of Congenital Anomalies Registry. Am J Cardiol 1990;65:793–97.

64. Suárez de Lezo J, Pan M, Romero M, et al. Immediate and follow-up findings after stent treatment for severe coarctation of aorta. Am J Cardiol 1999;83:400–6.

65. Chessa M, Carrozza M, Butera G, et al. Results and mid-long-term follow-up of stent implantation for native and recurrent coarctation of the aorta. Eur Heart J 2005;26:2728–32.

66. Shah L, Hijazi Z, Sandhu S, Joseph A, Cao QL. Use of endovascular stents for the treatment of coarctation of the aorta in children and adults: intermediate and midterm results. J Invasive Cardiol 2005;11:614–8.

67. Ledesma M, Alva C, Gómez FD, et al. Results of stenting for aortic coarctation. Am J Cardiol 2001;88:460–2.

68. Magee AG, Brzezinska-Rajszys G, Qureshi SA, et al. Stent implantation for aortic coarctation and recoarctation. Heart 1999;82:600–6.

69. Cheatham JP. Stenting coarctation of the aorta. Catheter Cardiovasc Interv 2001;54:112–25.

70. Ohkubo M, Takahashi K, Kishiro M, Akimoto K, Yamashiro Y. Histological findings after angioplasty using conventional balloon, radiofrequency thermal balloon, and stent for experimental aortic coarctation. Pediatr Int 2004;46:39–47.

71. Pedra CA, Fontes VF, Esteves CA, et al. Use of covered stents in the management of coarctation of the aorta. Pediatr Cardiol 2005;26:431–9.

72. Dean LS, Mickel M, Bonan R, et al. Four-year follow-up of patients undergoing percutaneous balloon mitral commissurotomy. A report from the National Heart, Lung, and Blood Institute Balloon Valvuloplasty Registry. J Am Coll Cardiol 1996;28:1452–7.

73. Latson LA, Prieto LR. Pulmonary stenosis. In: Allen HD, Gutgesell HP, Clark EB, and Driscoll DJ, editors. Moss and Adams' Heart Disease in Infants, Children, and Adolescents. Philadelphia, PA: Lippincott, Williams & Wilkins, 2001:820–44.

74. Nickerson E, Greenberg F, Keating MT, McCaskill C, Shaffer LG. Deletions of the elastin gene at 7q11.23 occur in approximately 90% of patients with Williams syndrome. Am J Hum Genet 1995;56:1156–61.

75. Oda T, Elkahloun AG, Pike BL, et al. Mutations in the human Jagged1 gene are responsible for Alagille syndrome. Nat Genet 1997;16:235–42.

76. Martin EC, Diamond NG, Casarella WJ. Percutaneous transluminal angioplasty in non-atherosclerotic disease. Radiology 1980;135:27–33.

77. Bergersen L, Gauvreau K, Lock JE, Jenkins KJ. Recent results of pulmonary arterial angioplasty: the differences between proximal and distal lesions. Cardiol Young 2005;15:597–604.

78. Bergersen L, Jenkins KJ, Gauvreau K, Lock JE. Follow-up results of cutting balloon angioplasty used to relieve stenoses in small pulmonary arteries. Cardiol Young 2005;15:605–10.

79. O'Laughlin MP, Perry SB, Lock JE, Mullins CE. Use of endovascular stents in congenital heart disease. Circulation 1991;83:1923–39.

80. O'Laughlin MP, Slack MC, Grifka RG, Perry SB, Lock JE, Mullins CE. Implantation and intermediate-term follow-up of stents in congenital heart disease. Circulation 1993;88:605–14.

81. Fogelman R, Nykanen D, Smallhorn JF, McCrindle BW, Freedom RM, Benson LN. Endovascular stents in the pulmonary circulation: clinical impact on management and medium-term follow-up. Circulation 1995;92:881–5.

82. Ing FF. Delivery of stents to target lesions: techniques of intraoperative stent implantation and intraoperative angiograms. Pediatr Cardiol 2005;26:260–1.

83. Hijazi ZM. Extracardiac fenestrated Fontan operation: to close or not to close the fenestration? Catheter Cardiovasc Interv 2001;54:88–92.

84. Beekman RH, Shim D, Lloyd TR. Embolization therapy in pediatric cardiology. J Interv Cardiol 1995;8:543–56.

85. Peng LF, McElhinney DB, Nugent AW, et al. Endovascular stenting of obstructed right ventricle-to-pulmonary artery conduits: a 15-year experience. Circulation 2006;113:2598–605.

86. Carvalho JS, Shinebourne EA, Busst C, Rigby ML, Redington AN. Exercise capacity after complete repair of tetralogy of Fallot: deleterious effects of residual pulmonary regurgitation. Br Heart J 1992;67:470–3.

87. Bonhoeffer P, Boudjemline Y, Saliba Z, et al. Transcatheter implantation of a bovine valve in pulmonary position: a lamb study. Circulation 2000;15:813–16.

88. Coats L, Khambadkone S, Derrick G, et al. Physiological and clinical consequences of relief of right ventricular outflow obstruction late after repair of congenital heart defects. Circulation 2006;113:2037–44.

89. Zhou JQ, Corno AF, Huber CH, Tozzi P, von Segesser LK. Self-expandable valved stent of large size: off-bypass implantation in pulmonary position. Eur J Cardiothorac Surg 2003;24:212–6.

90. Boudjemline Y, Schievano S, Bonnet C, et al. Off-pump replacement of the pulmonary valve in large right ventricular outflow tracts: a hybrid approach. J Thorac Cardiovasc Surg 2005;129:831–7.

91. Boudjemline Y, Agnoletti G, Bonnet D, Sidi D, Bonhoeffer P. Percutaneous pulmonary valve replacement in a large right ventricular outflow tract: an experimental study. J Am Coll Cardiol 2004;43:1082–7.