INTERVENTIONAL pediatric cardiac catheterization had its beginning in 1966, with the introduction of the balloon atrial septostomy by Dr. William Rashkind.1 In the past 25 years, significant and rapid progress has been made in the field of therapeutic catheterization in pediatrics. Such interventions conveniently can be divided into (1) opening things, (2) closing things, and (3) miscellaneous procedures. The purpose of this monograph is to describe the utility of interventional catheterization in pediatrics in those areas.

Opening Things

Balloon Atrial Septostomy

Since its introduction by Rashkind and Miller in 1966,1 balloon atrial septostomy has become a standard procedure for patients requiring intraatrial mixing or vent decompression of the right or left atrium. Examples of lesions which may require balloon atrial septostomy include transposition of the great arteries, tricuspid or mitral atresia, pulmonary atresia, total anomalous pulmonary venous return, and other complex cyanotic heart diseases including some forms of double-outlet right ventricle. In this procedure, a 4F or 5F balloon atrial septostomy catheter (USCI, Rashkind, Miller Edwards brand) is introduced percutaneously through a sheath from the femoral or umbilical vein and advanced to the right atrium, then positioned through the patent foramen ovale into the left atrium. It is inflated with 3 to 6 mL of diluted contrast material and rapidly jerked to the right atrium/inferior vena cava junction and then deflated. Although this procedure is usually performed in the catheterization laboratory, some cardiologists perform it in the neonatal intensive care unit with echocardiographic guidance. In our opinion, however, the standard catheterization laboratory method is preferred. The effective palliation rate in transposition of the great arteries with intact ventricular septum is approximately 90%. The experience at the Armed Forces Hospital in Riyadh since 1982 includes over 300 procedures with low morbidity. Reported complications include perforations of the atria, atrial lacerations (particularly the left atrial appendage), damage to atrioventricular valves, and inferior vena cava damage or thrombosis. Today's technique is essentially the same as that described in 1966.

Blade and Balloon Atrial Septostomy

If the atrial septum requires opening after the first one or two months of life, it may have become thickened and unresponsive to balloon septostomy alone. In 1973 Park et al2 described the use of a blade catheter for incising the atrial septum without the need for an operation. In this technique, a long sheath is positioned in the left atrium via percutaneous technique. The sheath may be advanced through an existing atrial septal defect (ASD) or patent foramen ovale which requires enlargement, or it may be placed into the
left atrium by transseptal technique. Once the 7F or 8F sheath is well into the left atrium, the Park blade catheter (William Cook Europe, Bjæverkov, Denmark) is advanced through the sheath into the left atrium. The catheter is a 5F or 6F, 65 cm long polyethylene tubing with the tip consisting of a 3.5-cm section of stainless steel tubing, containing a small collapsible blade. With the blade catheter in the left atrium, the sheath is withdrawn and the blade is opened by means of a lever at the proximal end of the catheter. The blade is pointed anteriorly (to the left or right), then is withdrawn slowly until the atrial septum is cut and the open triangular blade lies in the right atrium. Then the blade is closed and repositioned or withdrawn. Three to five cuts are required at different angles in order to incise the atrial septum appropriately. Afterwards, a balloon atrial septostomy is performed in the usual fashion. Indicators of a successful blade and balloon septostomy include increase in oxygen saturation, decrease in left atrial pressure, near equalization of right and left atrial pressures, and improvement in perfusion and respiratory status, depending upon the underlying lesion. Echocardiographic imaging can be used to size the ASD after its creation or enlargement.3 In some cases, blading can be performed through the native patent foramen ovale and additionally through a higher or lower transseptal puncture. This technique may permit the joining of two atrial defects into one large defect. In cases of mitral atresia, symptomatic relief may be attained with a residual pressure gradient of up to 10 mm Hg mean. In tricuspid valve atresia, pulmonary valve atresia, and total anomalous pulmonary venous return, the right atrial to left atrial pressure gradient should be reduced to 2 mm Hg mean or less. In transposition of the great arteries, left atrial pressure may be slightly higher than the right atrial pressure after an adequate septostomy is performed. Because of a multitude of catheter changes, blade septostomy carries an increased risk of blood loss and air or clot embolization. Meticulous attention to draining and flushing catheters and sheaths will reduce the incidence of this complication. Laceration of the heart, particularly of the left atrial wall or appendage, has occurred. The results of a collaborative study in 1982 demonstrated improvement in 79% of cases and excellent results over a four-year follow-up in 84%. There was a ten
dency for the intra-atrial opening to narrow in 16%. At Riyadh Armed Forces Hospital, 75 blade and balloon septostomies have been performed and the results are consistent with those of the collaborative study.

**Pulmonary Valve Stenotic Dilation**

The next cardiac structures which may require opening are valves. Balloon pulmonary valvuloplasty was described in 1982 by Kan5 and Pepine.6 Previously, pulmonary valve stenosis had required thoracotomy and open or closed pulmonary valvotomy to reduce right ventricular pressure and hypertrophy. With the percutaneous technique, the same opening can be achieved at cardiac catheterization. After clinical, electrocardiographic, and echocardiographic diagnoses are made of moderate-to-severe pulmonary valve stenosis, cardiac catheterization is performed. Pre-dilation gradients are measured, and angiography is performed. One or two end-hole catheters are positioned across the pulmonary valve into the right or left pulmonary artery, and wires are advanced through the catheters well into the pulmonary arteries. The positioning catheters are removed and one or two balloon dilatation catheters are advanced over the wires into position across the pulmonary valve annulus and inflated. When a single catheter is used, the balloon is chosen so that the nominal diameter of the balloon is 110% to 130% of the diameter of the annulus. For double-balloon dilation, the sum of the two balloons' diameters should equal 140% to 150% of the annulus diameter. The technique is applicable, even in the smallest infants with critical pulmonary valve stenosis. In some of these cases, sequential dilation, starting with coronary-sized wires and balloons, is required. Gradually, the opening will be enlarged to accommodate an 8-mm, 10-mm, or 12-mm balloon angioplasty catheter.7

In 232 procedures of pulmonary valve stenotic dilation performed at the Riyadh Armed Forces Hospital, the age ranged from 1 day to 12 years with a mean of 4 years. Twenty-three patients were less than one month of age while 84 patients were less than one year of age. The weight ranged from 2.4 to 47 kg with a mean of 13.7 kg. In the 232 procedures, the pre-valvulotomy peak systolic gradient ranged from 30 to 310 mm Hg with a mean of 97 mm Hg and a standard deviation of 49
mm Hg. After balloon valvulotomy, the gradients decreased to 0 to 175 mm Hg with a mean of 22 ± 17 mm Hg (77% reduction). Eighty-nine percent of patients had the gradient reduced by 50% or more; dysplastic pulmonary valves complicated the relief of gradient in some of the additional patients. Follow-up catheterizations in 103 patients demonstrated lasting relief of stenosis. A few patients required repeat balloon dilation, in some cases this was due to the use of inadequate sized balloons in the early experience.

Coarctation of the Aorta

In 1982 experimental and clinical uses of balloon dilation for postoperative coarctation of the aorta were described. After repair of coarctation, often required in infancy, there is a 20% to 40% incidence of restenosis. In the past, this required re-operation through an already scarred left thoracotomy area that had the potential for neurological and other complications. Since the general success of this technique, it has been extended to native or unoperated coarctations of the aorta. In this technique, retrograde heart catheterization is performed through the femoral artery, and angiography and pressure measurements across the coarctation are made. A wire is advanced through an end-hole catheter across the coarctation and into the ascending aorta. An appropriate-sized balloon catheter is advanced over the wire and centered across the coarctation and then inflated. In our opinion, the balloon should be chosen to equal the size of the isthmus, just distal to the origin of the left subclavian artery (if present) and proximal to the coarctation. After dilation the coarctation gradient and angiograms are repeated (Figure 1). Care is taken not to advance the catheter across a freshly dilated coarctation site, unless it is guided and protected by the retrograde wire. Excellent palliation has been achieved with coarctation dilation, both in native and postoperative cases. When there is a large patent ductus associated with coarctation, surgical division of the ductus and repair of the coarctation are recommended. However, if the ductus is small the coarctation can be dilated for palliation of congestive heart failure with no significant increase in ductal shunting. In infants undergoing balloon dilation of coarctation less than one month of age, even without a patent ductus.
there is a 70% to 80% recurrence rate of coarctation. The cardiologists and parents or patients are counselled that coarctation of the aorta may be a chronic or recurrent disease. With a judicious combination of coarctation surgery and balloon angioplasty, the aim of achieving an adult-sized aorta by adolescence may be realized in the majority of patients.

**Aortic Valve Stenosis**

Balloon dilation of congenital aortic valve stenosis has been performed with either single- or double-balloon technique. The indication for balloon dilation of aortic stenosis is the same as that for surgery, generally accepted to be a peak-to-peak pressure gradient across the valve of 50 mm Hg or greater with a normal cardiac output. The balloon size chosen for single-balloon dilation is 90% to 100% of the aortic valve annulus diameter and for double-balloon, 100% to 110%. Because of unavoidable temporary obstruction of the cardiac output during dilation, retrograde manipulation of wire and catheter, and working on the systemic side of the circulation, risks are somewhat greater than for pulmonary valve stenosis treatment. Risks include left ventricular perforation, aortic valve perforation or significant increase in aortic regurgitation, cerebrovascular accident, and femoral artery injury. Indeed, the double-balloon technique has the advantage of necessitating smaller catheters placed through femoral arteries bilaterally rather than one large catheter through one artery. Approximately 25% to 30% of patients develop some increase in aortic regurgitation after dilation, but generally this is well tolerated. Restenosis is uncommon, although it may occur as the patients grow. A similar technique has been proposed for thin membranous subaortic stenosis, although the consequences of leaving the sub aortic tissue in place versus resection are not entirely delineated. Balloon dilation of the aortic valve has the important advantage of delaying surgery until the patient is old enough to be able to accommodate an adult-sized prosthesis; in rare cases, surgery may be avoided altogether.

**Miscellaneous Dilations**

Although mitral valve stenotic dilation is common in patients with post-rheumatic carditis worldwide, there are only rare reports of dilation of congenital mitral valve stenosis. Although the mitral valve stenotic lesions in congenital heart disease often are complex, balloon dilation may prove a worthwhile palliation in many cases because of the difficulty of surgery and the wish to avoid valve replacement in infancy or early childhood. Tricuspid valve stenosis has been dilated in congenital heart disease only rarely. Other uses of balloon dilation include vena cava stenosis, particularly in patients submitted to Mustard operation, pulmonary vein stenosis, and pulmonary artery branch stenosis.

**Pulmonary Artery and Systemic Vein Stenotic Dilation and Stenting**

Only recently, intravascular stents are being utilized in pediatric cardiology. Experimental work initially showed feasibility of implantation and medium-term patency. In one experimental collaborative study in the United States, the Palmaz stent (Johnson & Johnson Interventional Systems) has been used in cases of pulmonary artery branch stenosis and venous anastomosis narrowings. In these lesions, balloon angioplasty alone is ineffective because of the natural or postoperative elastic recoil of the stenosis. After balloon dilation has demonstrated that the lesions will stretch to a certain size and return to the pre-dilation size as soon as the balloon is deflated, stent implantation is then considered. A 3-cm long stent with a 3.4-mm diameter is placed over a 10-mm or 12-mm diameter standard balloon angioplasty catheter and advanced through an 11 F sheath over a Super Stiff wire (Argon Inc., Athens, Texas, USA) across the stenosis. As the balloon is inflated, the stent expands with the balloon and remains in place as the balloon is deflated. The stent allows for support of the vascular wall after dilation. It has promise for important relief of stenoses in patients whose narrowings may otherwise be inoperable and untreatable. Additional follow-up and clinical work with the stents are required before definitive conclusions can be reached about their efficacy in congenital heart disease, although initial information is extremely promising.
Closing Things

**Patent Ductus Arteriosus**

In 1967 Portsmann et al. described a technique for occluding the ductus arteriosus non-surgically using a polyvinyl alcohol plug. This technique was cumbersome because of the large funnel required to be placed in the artery by the cut-down technique. In 1979 Rashkind and Cuaso described a double-umbrella device for catheter closure of patent ductus arteriosus (PDA). The procedure was further modified by Rashkind et al. and used clinically for PDA occlusion. In this procedure, a right-heart catheterization is performed and an 8F or 10F sheath is placed through the main pulmonary artery prograde across the PDA. A 12-mm or 17-mm occlusion device is then loaded onto a special delivery catheter and advanced through the sheath. After the distal umbrella is opened in the aortic end and fixed by manual traction into the ductus arteriosus, the proximal umbrella is then deployed in the pulmonary end. Once the device is confirmed in an appropriate position, a repeat aortogram is performed 15 minutes later. Although residual shunts through the polyurethane foam initially after implantation are common, they appear to seal spontaneously with endothelialization over the first few weeks or months. Embolization of the umbrella to the pulmonary artery or rarely to the descending aorta has been reported to occur in 5% to 7% of patients early in the experience of the operator. At our institution, there were seven cases of embolization in the first 160 implantations and none in the last 100 patients. Further refinements of the device design will likely reduce the incidence of residual shunts significantly.

**Atrial Septal Defect Closure**

Transvenous closure of a secundum ASD was first reported by King and Mills in 1972. In the late 1970s, Rashkind and Cuaso developed a single-umbrella prosthesis with hooks which were designed to lodge in the intra-atrial septum. Shortly thereafter, the Rashkind device was modified to a double-clamshell device with stainless steel arms supporting Dacron fabric umbrellas which faced one another. One umbrella was deployed on the left atrial side of a secundum ASD, and the other on the right atrial side, similar to the PDA occlusion technique. This device may be placed through an IIF sheath percutaneously and is able to effect closure of secundum atrial defects, from the smallest patent foramina oves up to 20-mm diameter secundum defects. With patients chosen appropriately, the success rate has been extremely good. More than 90% of patients have complete occlusion or only trivial left-to-right shunts after clamshell device implantation. At present, the ASD occluder is undergoing testing and scrutiny in the United States under a Food and Drug Administration protocol. Rare complications to the present time have included embolization and cerebrovascular accident. After the device has been implanted, some of the stainless steel support wires have fractured. This appears to be due to a realignment of the struts. There have been no shunt increases nor clinical sequelae from any of the numerous strut fractures. The clamshell device also has been used in selected cases of muscular ventricular septal defects and other postoperative shunts, including intentionally fenestrated Fontan repairs.

**Ventricular Septal Defect Closure**

Transcatheter closure of muscular ventricular septal defects (VSDs) was first attempted using the larger Rashkind occluding device. This device was utilized in some native muscular defects, in patch leaks in previously repaired VSDs and in some new VSDs in recent acute myocardial infarctions. Although the device and technique were successful in some cases, the device frequently was too small, resulting in significant residual leaks or actual embolization of the device. Some of the shortcomings of the PDA device were overcome by the larger sizes and by the design of the clamshell ASD device, making this a very useful technique for some otherwise difficult-to-treat defects.

Because the nature of and “hidden” location of the ventricular defects, the defects must first be crossed from the left ventricle to the right ventricle; and because of the apical and mid-muscular location of the defects, the device delivery usually
must be from the superior vena cava. This combination of circumstances results in a very complex and sometimes difficult delivery technique. This technique requires a "through and through" wire which is passed from either the venous approach via the atrial transseptal or arterial retrograde approach to the left ventricle, then through the ventricular septal defect into the right ventricle and from there back to the right atrium. This wire tip in the right atrium is snared by a second catheter which has been introduced into the right jugular vein. Once snared, the wire which has passed through the ventricular septal defect is drawn into the superior vena cava and from there out of a sheath in the right jugular vein. An IIIF long sheath/dilator set is then passed over this jugular/superior vena cava wire through the muscular ventricular defect and into the left ventricle. The dilator and wire are removed leaving the long sheath from the jugular vein as the delivery route. Thereafter, the loading of the device and the delivery is similar to the delivery to the ASD except the delivery of the device for the VSD is guided by transthoracic rather than transesophageal echo. When the risks are less than satisfactory, results from the surgical approach to the muscular ventricular defects are weighed against the risks and difficulties of the catheterization technique. It still appears that the transcatheter approach is a safer, more successful procedure with far less morbidity. In the collaborative study of the clamshell device, the success with the clamshell has been excellent with minimal morbidity or mortality in over 30 patients. Because of the complexity of the procedure it will certainly be limited to a few centers that are very active in therapeutic catheterizations.

**Coil Embolization**

Certain unwanted vessels such as aorto-pulmonary collaterals may be occluded with catheter techniques. Coil embolization was first described by Gianturco et al in 1975. Stainless steel coils are pre-formed using guidewire material, and Dacron strands attached along their length increase thrombogenicity. Coils come in various diameters, lengths, and thicknesses and are loaded into straight tubes by the manufacturer for insertion into and delivery through end-hole catheters. The coil is advanced out of its loader tube into the proximal end of a catheter by being pushed forward with an operator-controlled guidewire. Once the coil is extruded from the end of the catheter, it reforms to its nominal diameter (Figure 2). Because of the thrombogenic nature of
the coil and Dacron combination, occlusion generally will occur within five to fifteen minutes. Potential complications include embolization of the coils through the unwanted vessel into a distal normal pulmonary vessel or proximal embolization into the systemic circuit. The coil diameter should be 30% larger than the diameter of the vessel to be occluded. In general, the first coil delivered is the largest and prevents distal embolization, with subsequent smaller coils delivered to complete the occlusion.

Miscellaneous Procedures

Endomyocardial Biopsy

Transvenous endomyocardial biopsy was first introduced in Japan in 1962 and subsequently was modified by several investigators, with considerable improvement in recent years. The availability of thin, flexible biotomes and pre-formed long sheaths have increased the safety of the biopsy procedure, even in infants. Three accepted indications for endomyocardial biopsy in children are (1) myocarditis diagnosis, now potentially improved with the polymerase chain reaction technique, (2) cardiac transplant rejection detection, and (3) diagnosis and quantification of doxorubicin-induced myocardial disease. In general, four to six biopsy samples are obtained from the right ventricle, with the septal surface being targeted rather than the thinner anterior wall. In unusual cases in which right ventricular biopsy is not adequate, transseptal left heart catheterization and left ventricular biopsy may then be required. Complications have been few, although cardiac perforation, tamponade, and death have occurred. Other complications include pneumothorax (particularly with a jugular approach), atrioventricular block, arrhythmias, and air embolus.

Arrhythmia Ablation

Electrophysiological studies in patients with supraventricular and ventricular arrhythmias have permitted precise localization of re-entry pathways or ectopic foci. Preoperative and intraoperative mapping techniques have allowed the surgeon to successfully ablate these pathways and terminate the arrhythmia. Cardiac catheters have now been developed which can deliver radiofrequency energy to the endocardium to ablate bypass tracts, re-entry pathways, or ectopic foci which are localized by electrophysiological catheter mapping.

Foreign Body Retrieval

Catheter techniques have been devised for the retrieval and removal of foreign bodies such as fragments of polyethylene central venous catheters, guidewire fragments, and pacemaker catheter pieces. The foreign body is approached with a catheter and long sheath. Once the sheath is lodged against or near the foreign body, the guiding catheter is removed and a retrieval catheter (either a snare, wire basket, grabbing tool, or biopsy forceps) is introduced. With the foreign body ensnared or enmeshed by the retrieval catheter, the catheter and foreign body can be removed through the sheath without the need for a cut-down procedure of any type.

Conclusion

Over the past quarter of a century, interventional techniques in pediatric cardiology have been developed and refined to a great degree. Additional transcatheter techniques may be developed to augment or supplant surgery in selected cases. We have reviewed opening needed communications, closing unwanted communications, and miscellaneous procedures. Continued scrutiny and follow-up of these techniques will result in their continued improvement and refinement.

References