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New Therapeutic Avenues with Hybrid Pediatric Cardiac Surgery

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ABSTRACT

Background: Minimally invasive strategies can be expanded by combining standard surgical and interventional techniques.

Methods: A longitudinal prospective study was conducted of all pediatric patients who have undergone hybrid cardiac surgery at the University of Chicago Children's Hospital. Hybrid cardiac surgery was defined as combined catheter-based and surgical interventions in either one surgical setting or planned sequential surgical settings within a 24-hour period.

Results: Between June 2000 and June 2003, 24 patients were treated with hybrid approaches. Sixteen patients with muscular ventricular septal defects (VSDs) with a mean age of 4 months (range, 2 weeks to 4 years) underwent either sequential Amplatzer device closure in the catheterization laboratory followed by surgical completion (group 1A [n = 9]: right ventricular (RV) outflow tract enlargement, 6 patients; closure of other VSDs, 5 patients; tricuspid valvuloplasty, 3 patients; bidirectional Glenn shunt, 1 patient; Maze procedure, 1 patient; and retrieval of embolized device, 1 patient) or, more recently, a 1-stage intraoperative off-pump device closure (group 1B; n = 7) with the subsequent repair of concomitant heart lesions in 5 patients (double-outlet RV, 2 patients; arch hypoplasia/coarctation of the aorta, 2 patients; and pulmonary artery (PA) debanding, 1 patient). Cardioplegic arrest was either avoided or shortened in the muscular VSD patients. Eight patients with branch PA stenoses (group 2) underwent intraoperative PA stenting or stent balloon dilation along with RV outflow procedure (5 patients) or Fontan completion (3 patients with Maze procedure, mitral valvuloplasty, or Damus-Kaye-Stansel procedure in 1 patient each). All patients survived hospitalization. Complications from the hybrid approach in group 1A patients included tricuspid regurgitation in 2 patients, RV disk malposition in 1 patient, embolization of a VSD device into the aorta in 1 patient, and a residual VSD in 1 patient. No complications from the hybrid approach occurred in group 1B patients, and PA rupture from stent overinflation and ventricular dysfunction occurred in 1 patient each in group 2. During a mean follow-up period of 18 months (range, 2-36 months), 2 group 1A patients died suddenly several months after discharge. All of the other patients are doing well.

Conclusions: Hybrid pediatric cardiac surgery performed in tandem by surgeons and cardiologists is a safe and effective means of reducing or eliminating cardiopulmonary bypass. Patients with muscular VSDs who are small, have poor vascular access, or have concomitant cardiac lesions are currently treated in one setting with the perventricular approach.

INTRODUCTION

Although surgery remains the treatment of choice for most congenital cardiac malformations, interventional cardiology approaches are now increasingly used to treat simple and even complex lesions [Waight 2002]. However, the percutaneous approach can be challenging because of low patient weight or poor vascular access. In addition, the passage of large delivery catheters in small infants may result in rhythm disturbances and hemodynamic compromise. Furthermore, unusual septal planes, such as occur in patients with double-outlet right ventricle (DORV), D-transposition of the great arteries, or acute turns or kinks in the pulmonary arteries (PAs) in tetralogy of Fallot, can also make percutaneous procedures challenging, if not impossible.

On the other hand, surgery has its limitations. Examples are the operative closure of multiple apical muscular ventricular septal defects (VSDs), the adequate and lasting relief of peripheral pulmonic stenosis, and the management of a previously implanted stenotic stent [Serraf 1992, Kitagawa 1998, Seddio 1999]. Furthermore, in some complex malformations such as DORV, the presence of multiple muscular VSDs has been found to be an independent risk factor for early mortality [Aoki 1994, Kleinert 1997]. Thus, combining both surgical and interventional cardiologic venues in a single therapeutic maneuver or in short succession of maneuvers makes sense in a reduction in procedural complexity, bypass time, and risk and eventually improves the outcome.

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This report summarizes our experience with hybrid techniques in the management of congenital heart disease.

MATERIALS AND METHODS

All patients who underwent a hybrid pediatric cardiac procedure, defined as combined catheter-based and surgical interventions in a single setting or in planned sequential settings within 24 hours, between June 2000 and June 2003 were prospectively entered into a database. Twenty-four patients were treated with hybrid approaches. Procedures carried out via limited partial lower sternotomies, robotic approaches, and thoracoscopic procedures were not included in this study. Informed consent was obtained from the patients' guardians. The study was approved by the hospital investigation review board. A portion of this study was part of a US Food and Drug Administration Investigation Device Exemption clinical trial.

The patients were divided into 3 groups: group 1A, patients with muscular VSDs treated sequentially (n = 9); group 1B, patients with muscular VSDs treated concomitantly via a perventricular approach (n = 7); and group 2, patients with branch PA stenoses (n = 8)

Patients with Muscular VSDs

From June 2000 to October 2002, 9 patients with muscular VSDs in group 1A were treated in sequential fashion. The VSDs were closed in the catheterization laboratory with the Amplatzer congenital muscular VSD device (AGA Medical Corporation, Golden Valley, MN, USA), a self-expandable double-disk device made from nitinol wire mesh. The patients were then taken to the operating room for completion of the repair (Table 1A, Figure 1).

Group 1B comprised infants and children with muscular VSD treated since October 2002 and who also needed an additional surgical procedure (n = 7). These patients were taken to the operating room for perventricular closure of the muscular VSD and repair of the concomitant lesion (Table 1B). One patient also had an atrial septal defect that was closed via a peratrial approach (Figure 2). The heart was approached via a median sternotomy or via a subxyphoid minimally invasive incision without sternotomy if there were no other lesions. The best location for RV puncture was chosen under continuous transesophageal echocardiography (TEE) guidance, and attention was paid to be away from any papillary muscles but to be sufficiently far from the septum to enable a perpendicular approach to it with the needle and wire (Figure 3). A 5-0 polypropylene purse-string suture was placed at the chosen location. An 18-gauge needle (Cook, Bloomington, IN, USA) was introduced in the RV cavity and directed toward the defect to be closed. A 0.035-in angled Gidewire (Boston Scientific Medi-Tech, Natick, MA, USA) was passed through the needle and manipulated into the left ventricle (LV) cavity through the defect. A 7F to 10F catheter short (8-13 cm) introducer sheath with a dilator was fed over the wire and carefully advanced into the LV cavity. The dilator was removed, and the sheath tip was positioned in the LV cavity (Figures 2C and 3C). The appropriate device size was chosen to be 1 to 2 mm larger than the VSD size as assessed by TEE. The device was presoaked in nonheparinized blood for 10 minutes to allow the tiny fenestrations of the nitinol mesh to thrombose. The device was then screwed to the cable and pulled inside a 6F to 9F catheter loader under blood seal to prevent any air bubbles. The device was advanced inside the short delivery sheath until TEE monitoring indicated that it was close to the tip of the delivery sheath. The LV disk was deployed in the LV cavity by gentle retraction of the sheath over the cable. The entire assembly (cable and sheath) was withdrawn gently until the LV disk abutted the septum. Further retraction of the sheath over the cable would deploy the waist inside the septum. Continuous TEE monitoring to confirm the device position is of paramount importance. Once the position was confirmed, the sheath was retracted further to expand the RV disk. If the position was satisfactory, the device was released by rotating the cable counterclockwise with the pin vise. A complete TEE study in multiple planes was done to confirm device placement, to assess for residual shunting, and to ascertain whether any obstruction or regurgitation was induced by the device.

Patients with Branch PA Stenoses

An existing stent was dilated intraoperatively in 5 patients and was done if a stenosed PA stent could not be successfully accessed with the instruments via the percutaneous route (mostly because of acute angles of a branch PA vis-à-vis the main PA) (Table 2 and Figure 4).

A stent was placed in a branch PA in 3 patients for diffuse stenosis of the retroaortic portion of the PA, during a Fontan procedure in 2 patients, and for diffuse left PA stenosis in an older patient with tetralogy of Fallot (Table 2).

All of the patients with branch PA stenosis had a preoperative angiogram demonstrating the narrowing. The stent and balloon sizes were chosen by the cardiologist, and the choices were based on measurements made during this catheterization. Stents and balloons were placed under direct vision, and greater care was taken not to dissect the branch PA itself to ensure that the supportive tissue surrounding the vessel was maintained. The technical difficulty was in knowing how far to advance the stent into the branch PA without injuring the take-off of the lobar branches. Careful preoperative angiogram-based measurements are extremely important in planning how far to advance the stent inside the branch PA. Fluoroscopy was not used. Balloons were placed without a guidewire. The balloons were inflated to the manufacturer's recommended pressure for approximately 30 seconds.

RESULTS

Survival

All patients survived their hospital stays. Two patients in group 1A died suddenly at home at 8 months and at 12 months after discharge. Autopsies were not obtained. Both patients had presented with significant biventricular dysfunction in

Table 1A. Patients with Muscular Ventricular Septal Defects (VSDs) Who Underwent a Successive Interventional and Surgical Procedure*

Age/Weight	Diagnosis	Interventional Procedure	Complications	Surgical Procedures	Intraoperative Complications	Status at Follow-up (mo)
2 y/13 kg	DORV, apical VSDs, s/p repair, residual VSDs, supravalvular PS	Attempt at device closure of residual VSDs	No	VSD closure, PA plasty, pulmonary valvotomy	No	Well (34)
9 mo/4.1 kg	Anterior muscular, mid-muscular, and inlet VSDs, s/p PA band	Device closure of midmuscular VSD	No	Closure of residual VSDs, PA plasty and debanding	No	Well (35)
2 y/12 kg	Membranous VSD, apical muscular VSD, PS, s/p central shunt	Device closure of muscular VSD, pulmonary balloon valvotomy	No	Ligation central shunt, closure of membranous VSD, division of RVOT muscle bundles	No	Well (32)
4 mo/4.5 kg	Single apical VSD	Device closure	RV disk malposition with residual shunting	Apical VSD closure via apical right ventriculotomy	No	Well (36)
7 mo/6.9 kg	D-TGA, pulmonary atresia, inlet VSD, apical VSD, s/p BT shunt	Device closure of apical VSD (in preparation for 2-ventricle repair)	No	Cavopulmonary shunt	No	Well (18)
4 y/18 kg	Swiss cheese septum, s/p PA band, pulmonary HTN, tracheostomy	Multiple VSD device placement (complete closure)	TR (leaflet impingement from device)	PA plasty and debanding, TV repair	No	Well (36)
3 y/10 kg	Swiss cheese septum, s/p PA band, s/p debanding, PA aneurysm, atrial flutter	Multiple VSD device placement (partial closure)	TR (chordal rupture), embolized device in aorta	Device retrieval, VSD closure, TV repair, PA plasty, Maze	Residual VSD shunting	Sudden death at home (8)
4 y/24 kg	Swiss cheese septum, s/p PA band	Multiple VSD device placement (complete closure)	No	PA plasty and debanding	No	Moderate shunting across apical septum (16)
3 mo/3.4 kg	Biliary atresia, inlet and anterior muscular VSD, Ebstein anomaly, pulmonary HTN	Attempted device closure of muscular VSD	Ventricular tachycardia	VSD closures, TV repair	No	Sudden death at home (12)

*DORV indicates double-outlet right ventricle; s/p, status post; PS, pulmonary stenosis; PA, pulmonary artery; RVOT, right ventricular outflow tract; RV, right ventricle; D-TGA, D-transposition of the great arteries; BT, Blalock-Taussig; HTN, hypertension; TR, tricuspid regurgitation; TV, tricuspid valve.

Table 1B. Patients with Muscular Ventricular Septal Defects (VSDs) Who Underwent Perventricular VSD Device Closure*

Age/Weight	Diagnosis	Preoperative Symptoms	Exposure	Device Size	Additional Procedures	CPB†	Cardio-plegic Arrest	Intraoperative Complications	Qp/Qs	Postoperative Complications	Discharge Day	Echocardiography and Status at Follow-up (mo)
4 mo/4 kg	Anterior muscular VSD, ASD‡	FTT, CHF	Xyphoid incision	10 mm (VSD), 11 mm (ASD)	No	No	No	No	1.2	No	3	No shunt, asymptomatic (5)
17 d/3 kg	Large anterior muscular VSD	CHF	Xyphoid incision	12 mm	No	No	No	No	1.2	No	4	No shunt, asymptomatic (4)
20 d/3 kg	CoA + arch hypoplasia, large anterior muscular VSD, LV hypoplasia	Metabolic acidosis, cardiogenic shock	Median sternotomy	6 mm	CoA repair and arch augmentation	Yes	No	No	1.1	No	20	Tiny apical VSD, asymptomatic (7)
14 d/3 kg	Hypoplastic aortic arch + CoA, midmuscular VSD	Intubated, on PGE	Median sternotomy	8 mm	CoA repair and arch augmentation	Yes	No	No	1.2	No	18	No shunt, asymptomatic (2)
2.5 y/12 kg	s/p PA band for multiple apical VSDs	No	Median sternotomy	18 mm	Band removal and PA plasty	Yes	No	Difficult deployment of RV disk§	1.5	Reintubation for reperfusion pulmonary edema on POD 1	7	Residual (2 mm) VSD (5)
5 mo/7 kg	DORV, subaortic VSD, sub-PS/PS, multiple apical VSDs	No	Median sternotomy	8 mm	Subaortic VSD patch, pulmonary valvotomy, RV outflow patch	Yes	Yes	No	1.2	No	6	No shunt, asymptomatic (8)
3 y/20 kg	DORV, TGA, inlet VSD, apical muscular VSD, hypoplastic LV, s/p PA band and BDG	No	Median sternotomy	14 mm	VSD enlargement and LV-aortic baffle, t/d BDG‖	Yes	Yes	LV failure, ECMO; t/d of repair, removal of device and Fontan procedure	1.1	Pleural effusions	20	Widely patent ASD and VSD, asymptomatic (3)

*CPB indicates cardiopulmonary bypass; Qp/Qs, pulmonary blood flow–systemic blood flow; ASD, atrial septal defect; FTT, failure to thrive; CHF, congestive heart failure; CoA, aortic coarctation; LV, left ventricle; PGE, prostaglandin E; s/p, status post; PA, pulmonary artery; RV, right ventricle; POD, postoperative day; PS, pulmonary stenosis; DORV, double-outlet right ventricle; TGA, transposition of the great arteries; BDG, bidirectional Glenn shunt; t/d, take-down; ECMO, extracorporeal membrane oxygenation.

†CPB was needed only for additional procedures, not for placement of the device, which was done first in patients 3, 4, 5, and 6 and after PA band removal in patient 5. In patient 7, perventricular closure was accomplished on CPB because the decision to do it was made while the patient was on CPB.

‡Transesophageal echocardiography (TEE) results showed that the atrial septum had multiple separate openings. An aortic punch introduced via a right atrial puncture was used to create a central hole in the floppy septum primum. The technique described was used to position an 11-mm Amplatzer septal occluder to deploy it centrally in the ASD.

§The LV disk obliterated the entire left apical septum, resulting in no residual shunting. However, the RV disk was difficult to deploy because the severely hypertrophied moderator band and apical RV muscle bundles prevented the expansion of the RV disk. The RV disk was eventually positioned within the apical muscle bundles with the device microscrew protruding through the puncture site in the RV free wall. The screw was secured to the epicardium with a pledgeted suture. The Qp/Qs ratio at the end of the procedure was 1.5.

‖In preoperative studies, the apical muscular VSD was judged insignificant and was initially left alone. The failure of the patient to come off CPB after biventricular repair and TEE evidence of significant left-right shunting across the muscular VSD led to the decision to close the VSD with the perventricular technique. This procedure was successful in that TEE indicated the muscular VSD to be completely occluded, and the patient was weaned from CPB. LV hypoplasia prevented successful biventricular repair, and after a 24-hour period of rest on ECMO, the repair was taken down to an extracardiac Fontan procedure.

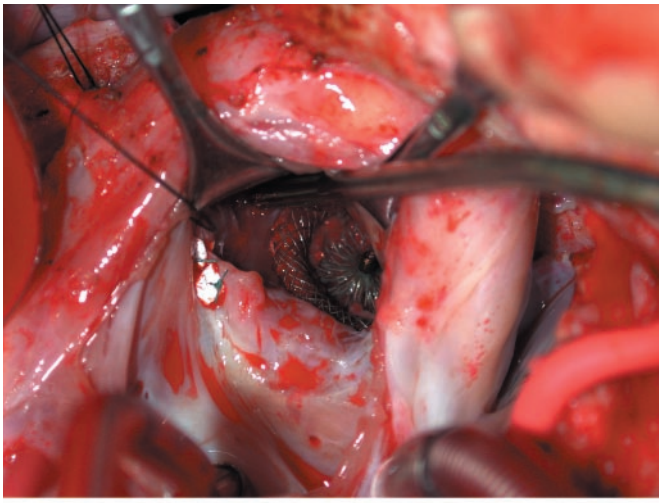

Figure 1. Intraoperative photograph of a child with subaortic ventricular septal defect (VSD) and a muscular VSD. The VSD device is seen in the muscular septum, and some of the sutures and pledgets used to suture the patch are seen at the anteroseptal commissure of the tricuspid valve.

addition to other complex malformations (Ebstein anomaly and pulmonary hypertension in 1 patient and atrial flutter in the other). One patient had been discharged with a significant residual apical VSD.

Complications from the Hybrid Technique

Group 1A had the largest number of complications. Complications from percutaneous device closure of muscular VSDs included tricuspid regurgitation in 2 patients (1 patient from leaflet impingement and 1 from chordal rupture), RV disk malposition in 1 patient, and device embolization into the aorta and ventricular tachycardia in 1 patient. Surgical complications included incomplete apical VSD closure in 1 patient.

Group 1B had few complications, most notably difficulties in 1 patient in the deployment of the RV disk because of a heavily trabeculated RV apex. Echocardiographic examination before patient discharge revealed only 1 patient with significant residual shunting across a muscular VSD. After a 5-month follow-up period, the residual VSD is now insignificant.

Group 2 patients had 2 significant complications. One was a left PA tear that occurred from the overdistention of a left PA stent. This tear was noticed intraoperatively and repaired by suturing a pericardial patch onto the tear. Another patient with an unbalanced atrioventricular canal and a ventricular outflow obstruction with ventricular dysfunction underwent a lateral tunnel Fontan procedure, a Damus-Kaye-Stansel procedure, and stent placement in the retroaortic PA. The patient was supported on extracorporeal membrane oxygenation (ECMO) for postcardiotomy syndrome and underwent successful heart transplantation after 3 weeks of ECMO support. We speculated that the retroaortic stent might have compressed the left main coronary artery, because a slight improvement in ventricular function occurred after tacking the PA superiorly. A subsequent catheterization procedure failed to show coronary compression.

Complications Not Related to the Hybrid Approach

One patient in group 1B had to be reintubated for reperfusion pulmonary edema that was successfully treated with inhaled nitric oxide. Another patient with DORV, a hypoplastic LV, transposition of the great arteries, and inlet VSD and who had undergone a bidirectional Glenn and a PA band procedure at another hospital had failure of a biventricular repair. In this patient, a small apical VSD became significant after the LV was pressurized, and the defect was closed with a device via a perventricular approach prior to weaning the patient from cardiopulmonary bypass. The repair failed because of LV dysfunction and hypoplasia. After a 24-hour period of support on ECMO, the repair was successfully taken down to a single-ventricle repair (extracardiac Fontan procedure), during which the muscular VSD device was removed.

DISCUSSION

The present study summarizes our institutional experience with hybrid cardiac surgery, in which surgeons and interventional cardiologists work in concert toward reducing operative trauma and improving outcomes. This approach is in line with a recent characterization of minimally invasive cardiac surgery [Chitwood 2003], and we believe that children should and will profit from such advances.

Efforts to combine catheterization and surgical techniques have been made before. For example, intraoperative balloon occlusions of Blalock-Taussig shunts and patent ductus arteriosus have been reported [Bhati 1972, Hjortdal 2002], and intraoperative balloon dilation of critical aortic stenosis in neonates and infants [Hussain 2002] and intraoperative stenting have also been described [Ungerleider 2001]. Several series of intraoperative closures of muscular VSDs with double-umbrella devices have also been reported [Fishberger 1993, Chaturvedi 1996, Okubo 2001]. The overall results were not satisfactory and had high mortality and failure rates. The approach common to all of these studies was that the devices were placed under direct vision with the patient in cardioplegic arrest. Difficulties in delivering the device or having to suture the device were specifically cited as factors in the poor outcomes. Interventional approaches are currently the preferred therapeutic approach for most muscular VSDs but are limited by several factors, such as patient weight, vascular access, and the need for surgical repair of concomitant lesions. Initially, we began a program of sequential management (group 1A) that eventually became obsolete as management evolved into a single procedure. We have recently reported our initial experience with this simplified technique of off-pump intraoperative device closure of muscular VSD via a perventricular approach [Bacha 2003]. This technique's safety has been validated in animal experiments [Amin 1999], and, in fact, the technique has been found to markedly reduce the complication rate (group 1A versus group 1B). The

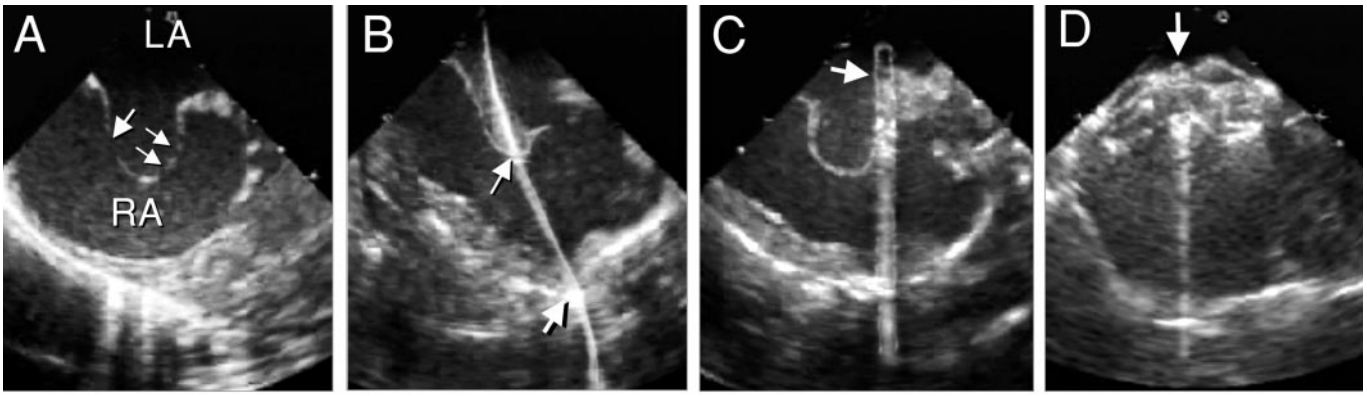

Figure 2. Closure with a peratrial atrial septal defect (ASD) closure device in a 4-month-old infant with a large multifenestrated ASD and anterior muscular ventricular septal defect. A, A transesophageal echocardiogram in the longitudinal plane demonstrating the presence of a large atrial septal aneurysm with a large superior defect (large arrow). B, Peratrial puncture (arrow) and passage of a wire through a hole created with an aortic punch. C, The sheath tip is positioned in the left atrium. D, Repeat image in the same plane after the deployment of an 11-mm Amplatzer septal occluder and demonstrating good device position and elimination of the aneurysm.

technique is simple and in all cases requires no more than 20 minutes to accomplish.

Many patients with muscular VSDs present with ventricular dysfunction and do better without prolonged catheterization and operative times. In fact, we believe that both of the patients in group 1A who died late might have fared better with a perventricular approach.

Advantages over an open repair include avoiding the transection of the moderator band or other RV muscle bundles, an immediate confirmation of adequate closure, and avoidance of

Table 2. Patients Who Underwent Intraoperative Stent Insertion or Stent Balloon Dilation for Branch Pulmonary Artery Stenoses*

Age/Weight	Diagnosis	Intraoperative Intervention	Additional Procedures	Intraoperative Complications	Status at Follow-up (mo)
7 y/25 kg	TOF, s/p repair, s/p LPA stent, PR	BD LPA stent	PV replacement	No	Well (1)
15 y/60 kg	TOF, s/p repair, s/p LPA stent, PR	BD LPA stent	PV replacement	No	Well (18)
2 y/18 kg	Tricuspid atresia, pulmonary atresia, severe AVVR	LPA stent	Fontan procedure, left AVV plasty	LPA tear, repaired with pericardial patch	Well (30)
9 y/22 kg	DORV, mitral atresia, atrial flutter, s/p central PA stent	BD central PA stent	Fontan procedure, Maze	No	Well (24)
2 y/11 kg	Unbalanced AVC, s/p Glenn shunt and PA band	Central PA stent placement	Fontan procedure, Damus-Kaye-Stansel procedure	Postcardiotomy syndrome, ECMO, heart transplant	Well (27)
2 y/11 kg	Truncus arteriosus, s/p repair, conduit stenosis, s/p bilateral PA stents	Bilateral BD PA stents	RV-PA conduit replacement	No	Well (19)
2 y/15 kg	Taussig-Bing heart/IAA, s/p repair, s/p LPA stent	BD LPA stent	RV outflow plasty	No	Well (12)
6 y/30 kg	TOF, s/p repair, multiple PA stenoses	LPA stent	MPA plasty	No	Well (32)

*TOF indicates tetralogy of Fallot; s/p, status post; LPA, left pulmonary artery; PR, pulmonary regurgitation; BD, balloon dilation; PV, pulmonary valve; AVVR, atrioventricular valve regurgitation; DORV, double-outlet right ventricle; AVC, atrioventricular canal; ECMO, extracorporeal membrane oxygenation; RV, right ventricle; IAA, interrupted aortic arch; MPA, main pulmonary artery.

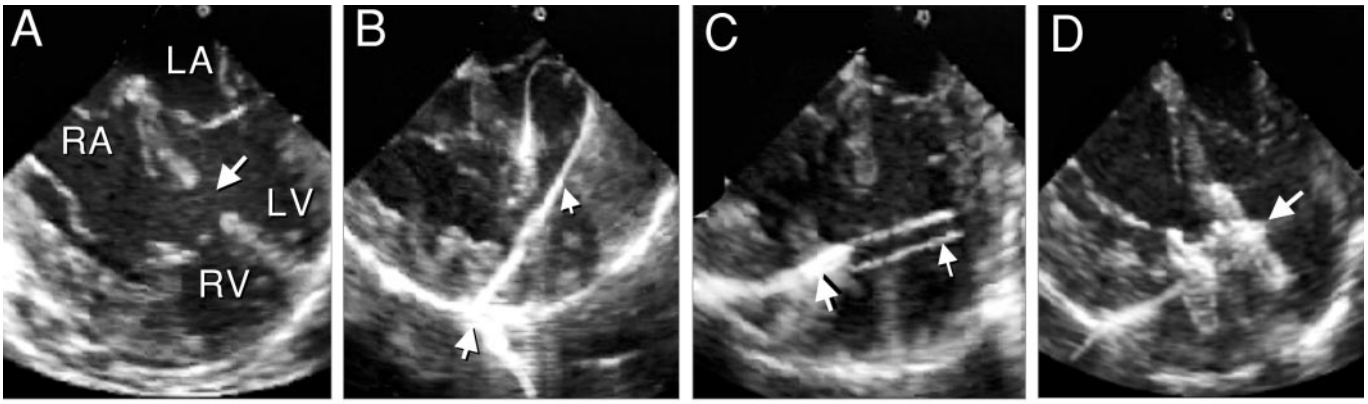

Figure 3. Closure with a perventricular ventricular septal defect (VSD) closure device in the same infant as in Figure 2. A, Large anterior muscular VSD (arrow). B, Perventricular puncture (arrow) and passage of a wire (arrow) across the VSD. C, The sheath tip is positioned in the left ventricular (LV) cavity, and the device (arrow) is introduced. D, Both disks have been deployed by pulling back the sheath. The device is still attached to the cable and can still be removed at this stage. LA indicates left atrium; RA, right atrium; RV, right ventricle.

any ventricular incisions. In the absence of associated defects, a minimally invasive approach, such as a subxyphoid incision (1-2 cm), can be easily used (2 patients in our series). Compared with percutaneous approaches, the hybrid approach has no weight limitations and no vascular-access limitations. In addition, the percutaneous closure of muscular VSDs in a child treated palliatively with a PA band often results in residual shunting after the PA band is removed. As the technique is illustrated here, the perventricular approach offers the possibility of debanding the PA and closing all VSDs in one setting. This technique can also be used for peratrial closure of atrial septal defects.

Patients with PA stenoses can also benefit from a hybrid approach. Single-ventricle patients with a large reconstructed ascending aorta, such as occurs after Norwood-style reconstruction, often have compression of the retroaortic portion of the branch PA. It is time-consuming to dissect out that area for patching, and dissection can also result in injury to the left main coronary artery. Delivery of a stent under direct vision via the opened right PA is simple and can be done on the beating heart or even off-pump if a source of pulmonary blood flow such as a cavopulmonary connection is present [Petrossian 2000]. However, stent compression of the left main coronary artery, which is also well described in the interventional literature, should be carefully avoided by not overdilating the stent [Mendelsohn 1993]. Fluoroscopy, although not used in this series, may be a very useful tool to have to ensure the correct positioning of the stent prior to dilation.

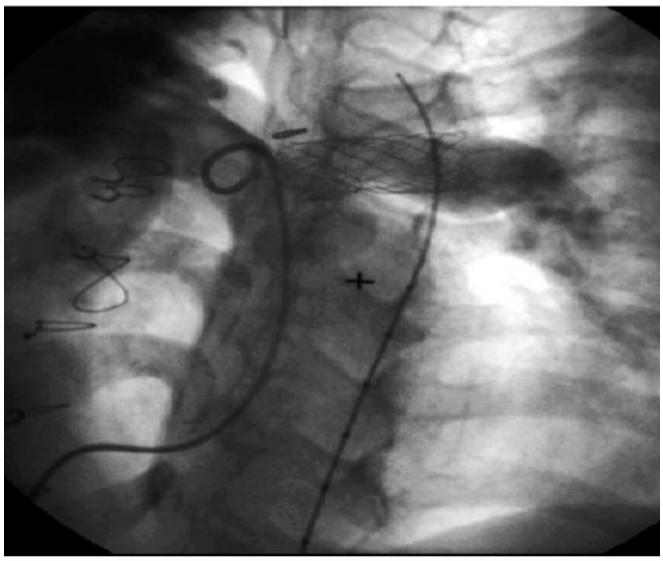

Figure 4. Preoperative angiogram in an older child status post repair of tetralogy of Fallot and left pulmonary artery (PA) stent. The angle between the main PA (pigtail catheter) and the stented left PA was acute and could not be crossed during catheterization. This child underwent intraoperative balloon dilation of the stent.

In conclusion, this study, although not randomized, supports the notion that hybrid pediatric cardiac surgery performed in tandem by surgeons and cardiologists is safe and effective in reducing or eliminating cardiopulmonary bypass. We believe that perventricular muscular VSD closure should be the treatment of choice for any infant with muscular VSDs, for older children with poor vascular access, and for patients previously treated palliatively with PA bands. In addition, intraoperative PA stenting is a valuable addition to the surgeon's armamentarium. As experience in hybrid cardiac surgery is gained, directly visualized thoracoscopic or robotic delivery of a device into a PA or a septal defect via puncture may soon be a reality.

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