Hybrid pediatric cardiac surgery is an emerging field that combines skills and techniques used by pediatric cardiac surgeons and interventional pediatric cardiologists. This article describes the emerging indications and techniques in hybrid pediatric cardiac surgery and discusses potential future applications. It focuses on peratrial and perventricular septal defect closure, intraoperative stenting, hybrid stage I palliation for hypoplastic left heart syndrome, and percutaneous valve implantation.

KEYWORDS: Hybrid pediatric cardiac surgery

The best way to predict the future is to create it.
Peter F. Drucker 1909–, Author and Business Philosopher

A close collaboration between congenital heart surgeons and interventional cardiologists has traditionally been a hallmark of the management of difficult lesions, such as tetralogy of Fallot with pulmonary atresia. However, work was mostly done in sequence. Hybrid pediatric cardiac surgery is an emerging field that reaches across interdisciplinary lines and combines skills and techniques traditionally used by pediatric cardiac surgeons and interventional pediatric cardiologists into, ideally, a single procedure. The goal of hybrid pediatric cardiac surgery is to reduce the magnitude of therapeutic interventions on children by decreasing their numbers or their invasiveness or by increasing their effectiveness by opening new therapeutic possibilities. A key difference with conventional minimally invasive surgery is the extensive use of intraoperative imaging techniques, such as fluoroscopy or transesophageal echocardiography (TEE) used on the beating heart while performing a given task, as opposed to working on an arrested flaccid heart and “checking the result” afterward. Thus, hybrid techniques are especially useful in the following two scenarios: (1) when surgery or catheter-based interventions alone are not achieving a satisfactory result for a given problem and (2) when the combination of the two fields results in less invasiveness and less trauma to the patient.

This article focuses on recent and future developments in hybrid procedures for the management of certain congenital cardiac defects.

Perventricular Ventricular Septal Defect Closure

Although surgical results for multiple muscular ventricular septal defects (muscVSDs) have improved recently in terms of hospital survival\textsuperscript{1,2}, the need for ventriculotomies\textsuperscript{2-4}, palliative procedures such as pulmonary artery (PA) banding, and a persistent rate of residual VSDs remains significant. In addition, the presence of associated muscVSDs with complex lesions such as transposition of the great arteries or double-outlet right ventricle has long been recognized to be an independent risk factor of early mortality.\textsuperscript{5,6} During surgery, some muscVSDs may never be found despite searching by extensive resection of muscular trabeculations. This emphasizes the need for an approach that allows for VSD closure with real-time visualization on a beating euvolemic heart. Isolated muscVSDs can be surgically closed with excellent overall success, but the majority of these patients are being managed by the percutaneous approach, which, over the last few years, has become increasingly popular.\textsuperscript{7} A recent report on mid-term results of a United States registry of 69 patients revealed a hospital mortality of 2.9% and a major complication rate of 11%.\textsuperscript{8} Complete closure was achieved in about half the patients at 24 hours and in >90% of patients at 12 months follow-up. That report and others\textsuperscript{9} showed that the chances of procedural success are limited by patient weight or by VSD size. The interventional approach is further limited by vascular access problems in patients who have often had many interventional procedures. Finally, many patients with
muscVSDs have been banded or have concomitant lesions that require surgical repair. The safety of perventricular puncture and device delivery has been validated in animal experiments. Current indications for the perventricular closure of muscVSDs include any infant weighing >5 kg or any child with associated muscVSDs and other cardiac defects requiring simultaneous repair, such as PA debanding, double outlet right ventricle, coarctation, or transposition of the great vessels. There are no absolute contraindications to this technique.

**Technique**

The technique has been described elsewhere. Briefly, under continuous TEE guidance and via a median sternotomy, or a subxiphoid minimally invasive incision (if there are no other lesions), the best location for right ventricular (RV) puncture is chosen. A purse-string suture is placed, the RV is punctured using an 18G needle (Cook Inc., Bloomington, IN), and an 0.035-inch short guide wire is passed through the VSD. Once the wire tip is positioned in the left ventricular (LV) cavity, the needle is removed, and a short, proper size, introducer sheath with a dilator is fed over the wire and advanced into the LV cavity. Extreme care is exercised not to advance the sheath with the dilator too far into the LV cavity because of the risk of perforation. The dilator is removed, and the sheath is de-aired. The proper size device (usually 1-2 mm larger than the size of VSD at end diastole) is chosen. The device used is the Amplatzer MVSD device (AGA Medical Corporation, Golden Valley, MN). The device is pre-soaked in nonheparinized blood, screwed to the cable, and pulled inside a loader. It is then advanced inside the short delivery sheath until the LV disk opens up in the LV cavity by retraction of the sheath over the cable. The entire assembly is withdrawn until the LV disk abuts the septum. Further retraction of the sheath over the cable deploys the waist and then the RV disk (Fig 1). At that stage, the device can still be re-captured into the delivery sheath if the device position is unsatisfactory. If the position is satisfactory, the device is released by counterclockwise rotation of the cable using a pin vise. A complete TEE study in multiple planes is done to confirm proper device position and to assess for residual shunting and any obstruction or regurgitation induced by the device.

**Advantages, Disadvantages, and Pitfalls**

The advantages of this technique over standard surgical techniques include the real-time feedback obtained by continuous TEE monitoring during perventricular device closure. Precise identification of VSD rims, residual shunts, device malposition, or atrioventricular (AV) valve problems secondary to chordal impingement by the device can be diagnosed in real-time and corrected. Further advantages include avoidance of cardiopulmonary bypass (CPB) in patients with isolated muscVSDs or, if associated cardiac lesions are present, marked reduction in CPB and myocardial ischemia time. Other advantages include avoidance of any ventricular incisions or muscle transections.
Compared with percutaneous approaches, it has no weight and no vascular access limitations. Crossing muscVSDs percutaneously in patients with unusual septal planes, such as double outlet right ventricle or transposition of the great arteries, can be challenging. By using the direct access per-ventricular technique, the septum is approached from a perpendicular angle, allowing for a “straight shot” at the VSD and less need, if any, for torque. However, even with a per-ventricular approach, some VSDs may not be easy to cross. In this situation, we have used percutaneous femoral arterial access to cross the VSD with a wire from the left side under fluoroscopic guidance. Using a gooseneck snare (ev3 Inc., Plymouth, MN) introduced into the PA via a percutaneous RV puncture, the wire is snared under fluoroscopy and exteriorized out the right ventricle free wall creating an arterio-right ventricular loop. Over this wire, the short delivery sheath is guided to cross the VSD into the LV cavity, enabling device placement as described previously. Finally, percutaneous closure of muscVSDs in a banded child often results in residual shunting after the PA band is removed in the OR. The present technique offers the possibility to de-band and reconstruct the PA and then close all VSDs in one operative setting on the beating heart.

Pitfalls include difficulties with the RV disk expansion in patients with RV hypertrophy. The RV disk may not expand completely, and the screw sometimes protrudes through the puncture site. We have dealt with this problem by suturing the tip (microscrew) of the device to the epicardium with a simple pledgetted stitch placed on the beating heart. This was performed in two patients with a follow-up of 3 and 22 months, respectively. No complications have been observed. Another alternative is to use an Amplatzer duct occluder device, which looks like a mushroom with a large “left-sided” disk and a stalk (no disk) for the right side. Finally, during the LV disk deployment, the mitral subvalvar apparatus may get entangled in the device. This should be recognized immediately on the TEE and dealt with by recapturing the disk and re-deploying it away from the mitral valve apparatus. Our current patient experience (n = 10) is detailed in Table 1.

**Intraoperative Stenting**

Patch enlargement of branch PA stenosis or pulmonary vein ostial stenosis can be time consuming and technically challenging. Along with intraoperative balloon dilation of recurrent coarctation, intraoperative stent implantation into branch PAs or pulmonary veins can be viewed as one of the earliest attempts at hybrid surgery. Experience with intraoperative stenting of pulmonary veins is mixed at best and cannot be recommended. The indications for intraoperative PA stenting are patients with limited vascular access and patients who need concomitant surgical procedures. Dissection around the segment to be stented should be avoided in case transmural tears occur. The stents can be placed on the arrested heart with the main PA opened. This allows for cardiac endoluminal visualization of the stent position, including the lobar branch ostia. They can also be placed on the beating heart via a puncture of the RV outflow or the main PA, using fluoroscopy to determine placement. An initial angiogram is performed, followed by passage of a wire into the desired branch and stent deployment using standard catheter techniques. This allows for precise positioning in relation to the hilar branches and solves one of the major problems associated with intraoperative stenting on the arrested heart; namely, during insertion, the distal portion of the balloon and stent cannot be seen directly and thus could tear the vessel if expanded in a lobar branch orifice. From the available literature and our own experience with nine patients, ideal candidates are older children with diffusely small branch PAs that have failed surgical patch angioplasty or children in whom the retroaortic PA is compressed by a large neo-aorta. We have found that direct cardiac access stent implantation on the beating heart under fluoroscopic control provides the most control. Small stents (10 mm or smaller) should be avoided because they lead to in-stent stenosis; thus, this procedure should be avoided in small children. Another potential pitfall is that stenting of the retroaortic PA may result in left coronary artery compression.

**Hybrid Palliation for Hypoplastic Left Heart Syndrome and Other Single-Ventricle Anomalies**

Despite recent improvements in survival rates, the Norwood Stage I operation remains a high-risk endeavor characterized by invasive neonatal procedure that requires prolonged cardiopulmonary bypass with occasional deep hypothermic circulatory arrest, multiple blood transfusions, prolonged intensive care recovery, and delayed sternal closure. When compared with infants, neonates have been shown to have reduced immune defenses ans diastolic function and greater propensity to capillary-leak syndrome. Risk factors for dying or serious morbidity include presentation with shock, birth weight <2.5 kg, prematurity <34 weeks gestational age, age >30 days, aortic atresia, poor ventricular function, tricuspid regurgitation, or serious noncardiac malformations. Although the significance of some of these risk factors, espe-
Table 1 The University of Chicago Experience With Perventricular VSD Closure (09/02–10/04) (10 Patients)

<table>
<thead>
<tr>
<th>Age</th>
<th>Weight</th>
<th>Diagnosis</th>
<th>Device Size</th>
<th>Additional Procedures</th>
<th>CPB*</th>
<th>Cardioplegia</th>
<th>Intraoperative Complications</th>
<th>Postoperative Complications</th>
<th>Echo and Status at F/U (mos)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated muscular VSD in infants†</td>
<td>17 d</td>
<td>Large anterior muscle VSD</td>
<td>12 mm</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No shunt asympt.⁰²</td>
</tr>
<tr>
<td></td>
<td>3 kg</td>
<td>4 mo</td>
<td>Anterior muscle VSD, ASD</td>
<td>10 mm (VSD)</td>
<td>11 mm (ASD)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No shunt asympt.⁰²</td>
</tr>
<tr>
<td></td>
<td>4 kg</td>
<td>4 mo</td>
<td>Two large anterior VSDs, multiple apical VSDs</td>
<td>10 mm (PDA device)</td>
<td>8 mm</td>
<td>Perventricular arteriovenous loop (see text)</td>
<td>No</td>
<td>No</td>
<td>1st device recaptured and exchanged for PDA device</td>
</tr>
<tr>
<td></td>
<td>5.5 kg</td>
<td>5.5 kg</td>
<td>Isolated muscular VSD in infants†</td>
<td>17 d</td>
<td>4 m</td>
<td>4 k</td>
<td>No</td>
<td>No</td>
<td>No shunt asympt.²²</td>
</tr>
<tr>
<td></td>
<td>4 mo</td>
<td>5.5 kg</td>
<td>Two large anterior VSDs, multiple apical VSDs</td>
<td>10 mm (PDA device)</td>
<td>8 mm</td>
<td>Perventricular arteriovenous loop (see text)</td>
<td>No</td>
<td>No</td>
<td>1st device recaptured and exchanged for PDA device</td>
</tr>
<tr>
<td></td>
<td>16 d</td>
<td>3.1 kg</td>
<td>Aortic CoA+arch hypoplasia</td>
<td>8 mm</td>
<td>Coarctation repair and arch augment</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No shunt, asympt.¹⁷</td>
</tr>
<tr>
<td>Muscular VSD with other surgical lesions: Coarctation of the aorta/muscular VSD in neonates</td>
<td>14 d</td>
<td>Hypoplastic aortic arch + coarctation, mid-muscle VSD</td>
<td>8 mm</td>
<td>Coarctation repair and arch augment</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No shunt, asympt.¹⁷</td>
</tr>
<tr>
<td></td>
<td>4.2 kg</td>
<td>20 d</td>
<td>Aortic CoA+arch hypoplasia, large anterior muscle VSD, LV hypoplasia</td>
<td>6 mm</td>
<td>Coarctation repair and arch augment</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No shunt, asympt.²³</td>
</tr>
<tr>
<td></td>
<td>3 kg</td>
<td>16 d</td>
<td>Hypoplastic aortic arch + coarctation, mid-muscle VSD</td>
<td>8 mm</td>
<td>Coarctation repair and arch augment</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No shunt, asympt.²³</td>
</tr>
<tr>
<td>Muscular VSDs s/p PA band</td>
<td>3 yr</td>
<td>S/p PA band for posterior muscle VSD</td>
<td>14 mm</td>
<td>Band removal and PA plasty</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No resid. VSD asympt.¹⁴</td>
</tr>
<tr>
<td></td>
<td>15 kg</td>
<td>2.5 yr</td>
<td>S/p PA band for multiple apical VSDs</td>
<td>18 mm</td>
<td>Band removal and PA plasty</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No resid. VSD, asympt.²²</td>
</tr>
<tr>
<td></td>
<td>12 kg</td>
<td>2.5 yr</td>
<td>S/p PA band for multiple apical VSDs</td>
<td>18 mm</td>
<td>Band removal and PA plasty</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No resid. VSD, asympt.²²</td>
</tr>
<tr>
<td>Other infants and children</td>
<td>3 yr</td>
<td>DORV, TGA, inlet VSD, apical muscle VSD, hypoplasia LV, s/p BDG</td>
<td>14 mm</td>
<td>VSD extension LV-aortic baffle, t/d BDG</td>
<td>Yes</td>
<td>Yes</td>
<td>LV failure, ECMO; t/d of repair, device removal, Fontan</td>
<td>Pleural effusions</td>
<td>Widely patent ASD and VSD asympt.¹⁰</td>
</tr>
<tr>
<td></td>
<td>20 kg</td>
<td>5 mo</td>
<td>DORV, subaortic VSD, subPS/PS, multiple apical VSDs</td>
<td>8 mm</td>
<td>Subao. VSD patch, pulm. valvot., RV outflow patch</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No shunt, asympt.²⁵</td>
</tr>
</tbody>
</table>

Abbreviations: ASD, atrial septal defect; BDG, bidirectional Glenn shunt; BTS, Blalock-Taussig shunt; CHF, congestive heart failure; coarct., coarctation; CPB, cardiopulmonary bypass; augment., augmentation; D/C, discharge; FTT, failure to thrive; hypoplasia; LV, left ventricle; valvot., valvotomy; PA, pulmonary artery; PDA, patent ductus arteriosus; PS, pulmonary stenosis; POD, post-operative day; reperf., reperfusion; RV, right ventricle; s/p, status post; t/d, take-down; VSD, ventricular septal defect; asympt., asymptomatic.


*Cardiopulmonary bypass was needed only for additional procedures, not for placement of the device.

†All three via minimally-invasive xiphoid incision.
cially aortic atresia, has been argued, given the available survival rates for these high-risk patients, a less invasive method of stage I palliation should be beneficial. Furthermore, neurologic development of the survivors in relation to prolonged neonatal CPB or hospitalization in the setting of cyanosis and low cardiac output remains an issue.16-21

Branch PA banding is one of the earliest methods of stabilization and remains popular today in specific situations.22,23 Encouraged by initial success of ductal stenting, some groups in Europe began using the strategy of percutaneous ductal stenting followed by surgical band placement for initial palliation of hypoplastic left heart syndrome.24,25 This strategy could lead to a percutaneous Fontan completion,26,27 with one major on-pump reconstruction sandwiched between two interventional procedures.

### Technique

The procedure is performed in the catheterization laboratory, which is prepared by having the surgical nursing team set up instruments as if in the operating room. The ECMO team remains on stand-by. A TEE probe is placed unless the atrial septum is judged to be nonrestrictive on surface echo. Under usual monitoring, chest, abdomen (incorporate umbilical lines in the field), and groins are prepped and draped. A median sternotomy is performed, and the thymus is subtotally resected. The chest retractor is placed in such a way as to be able to remove it when fluoroscopy is performed. The pericardium is opened excentrically and not resected. Stay sutures are placed. A 1.5-mm wide ring is cut off a standard 3.5-mm Gore-Tex tube graft (W.L. Gore & Associates, Inc., Flagstaff, AZ) and cut open. A 5-0 polypropylene mattress suture is placed through one end of the cut ring. The right PA is encircled to the right of the ascending aorta, and the Gore-Tex band is pulled through using the arms of the 5-0 suture. The suture is passed through the other end of the band and tied. Small size clips are placed over the sutured portion, and more clips can be used to tighten further, if necessary. The left PA is similarly banded at its origin. It is important to not dissect the branch PAs more than necessary to use the surrounding tissues as buttress against banding. Next a 5-0 polypropylene purse-string is placed at the sino-tubular junction of the main PA. The main pulmonary artery is punctured using a 21G needle (Cook Inc., Bloomington, IN), and a 0.018-inch short guide wire is passed into the descending aorta via the ductus. A short 6Fr sheath is advanced over the guide wire. The stent is placed so that the distal end of it is just protruding into the descending aorta and the proximal part is just above the branch PA openings. We have been using the Precise (Cordis; Johnson & Johnson, Warren, NJ) or Protégé (ev3 Inc, Plymouth, MN) stents. Once the stent is deployed, repeat angiogram is performed to assess the position of the stent, the bands, and the aortic arch.

If the stent is not covering the entire ductus, another stent is deployed to overlap the first stent (one case in our experience). If the pulmonary artery bands are deemed to be too tight or loose, they can be adjusted accordingly. We prefer the diameter of the banded portion of the PA to be approximately 30% to 40% of the diameter of the proximal PA (Fig 2). If the atrial septum is restrictive, the atrial communication can be enlarged using a self-expandable stent, or a balloon atrial septostomy is performed from the umbilical vein under fluoroscopic guidance. We have deployed atrial septal stent via a peratral puncture similar to the technique described for closure of an ASD in two patients. Most patients were receiving low FiO₂ (mean 23%, range 21-30) at the beginning of the procedure and left the catheter laboratory at slightly higher FiO₂ (mean 30%, range 21-50, P = NS) with oxygen saturations in the mid-eighties.

### Results

Between November 2003 and November 2004, we performed 11 hybrid stage I procedures consisting of single-stage ductal stenting and bilateral branch PA banding. The mean weight was 2.8 kg (range 2.2-3.3 kg), and the mean age was 5.7 days (range 1-17 days). Pre-operative risk factors were present in all patients and included aortic atresia in seven, weight <2.5 kg in three; severe noncardiac genetic anomaly in two; and prematurity (<34 weeks gestational age). Intact atrial septum, intracerebral bleed, presentation in shock, LV-coronary fistulae, partial left diaphragmatic hernia, intestinal pneumatosis, and poor ventricular function in one each, respectively. Intraoperative complications occurred in one patient who suffered cardiac arrest; the patient required ECMO and subsequently required a heart transplant. This patient died of sepsis at 8 weeks of age. All the other patients had their chests closed primarily, and none required an increase in or initiation of inotropic support. Hospital survival after hybrid stage I was 9/11 patients (81%). There were two ductal stents migrations: One was fatal, and the other required repeat percutaneous stenting. Bands had to be revised (typically tightened) in the first four patients. Since adopting the method of completion angiogram to check the bands (see above), we have not had to revise bands in the last six patients. There was one interstage fatality from atrial stent migration. Six patients underwent a stage II reconstruction consisting of stent removal, aortic arch reconstruction, and cavopulmonary shunt. Five survived, and one died from superior vena cava thrombosis related to heparin-induced thrombocytopenia. One later died at home at age 8 months from an infection likely related to severe immunodeficiency from DiGeorge-related T-cell malfunction. Two patients are currently awaiting stage II.

### Advantages, Disadvantages, and Pitfalls

Our results reflect a steep learning curve. Nevertheless, despite this being a pilot series of consecutive patients, out-
comes have been in the range of those seen by the majority of programs who perform a stage I Norwood procedure for high-risk patients. Problems that have emerged from this series have been:

1. Ductal stent migration (two cases, including one death). We now routinely measure the ductal width by angiogram and oversize by 1-2 mm. Because of the large ductuses associated with interrupted aortic arch, we view this entity as a contraindication to ductal stenting.

2. Atrial stents performed well in the short term but poorly in the long term (>8-12 weeks). Two patients had stent migration; one died at home, and the other required open surgical septostomy. We do not rely on atrial stents for more than 3 months. Elective stage II is scheduled for 3 months of age, and we keep a close eye on these patients by weekly echocardiograms. As part of an interstage monitoring protocol, an angiogram is performed at 6 weeks of age in preparation for stage II. Patients who had no interventions initially on their atrial septum can be balloon dilated or stented at that time.

3. Difficulties in left PA reconstruction (two patients required left PA stenting shortly after stage II). We now routinely patch the left PA at the time of stage II.

4. Potential problems of retrograde flow into the arch in aortic atresia. We have not seen this problem, but one of the patients had a 3-mm opening into his arch at the time of stage II.

5. Postoperative care: Overall, the procedure was not difficult to learn, and the postoperative care is benign. Most patients were extubated shortly after the procedure.

6. The stage II reconstruction is a challenging operation. However, the physiologic reserve of a 3-6 month-old is greater than that of a neonate. Furthermore, assuming the technical aspects (mainly aortic arch reconstruction) are mastered, the patient is left postoperatively with a circulation in series and not in parallel as after the Norwood stage I and is thus easier to manage.

**Percutaneous Valve Implantation**

Percutaneous valve implantation has been successfully performed in the aortic and pulmonary position. Surgeons need to be acutely aware of ongoing efforts and become pioneers in this field because they have invaluable decades-old expertise, they will have to manage the complications that will undoubtedly occur, they may have to modify right ventricular outflow tract reconstruction into a specific set-up that allows for future percutaneous implants in the case of growing children, and they may be called upon for direct access transcatheter valve placement. In pediatrics, peripheral vascular access is a major issue for insertion of the larger introducer systems that percutaneous valves require. Valved stents inserted through the groin have to travel over a long path to reach the target zone, which is usually the level of the annulus of the native or prosthetic valve. Long delivery systems must be flexible enough for steerability but rigid enough to have good torque and resistance to kinking. Having to negotiate these systems safely through AV valves can be
challenging. Until new technologic advances solve these problems, direct access to the heart may be a better approach. This can be accomplished via full sternotomy, thoracic mini-incisions (such as a subxiphoid incision for access to the right ventricle), or a trans-apical approach. The latter can potentially be performed with robotic or thoracoscopic assistance. Direct implantation without sutures via aortotomy on cardiopulmonary bypass has also been reported. Direct access to the heart has a number of advantages over remote access, including shorter delivery systems and no size limitations. This translates into higher-quality devices (less need to miniaturize), better delivery systems, overall ease of implantation, and reduced complications. Recently, device closure of the perventricular puncture site was introduced. This may allow for easier control of cardiac puncture sites via minimally invasive techniques.

Research and Development

To progress further, hybrid techniques will rely heavily on new development of technologies in multiple areas that may not be directly related to cardiac surgery, such as devices (absorbable stents for temporary ductal stenting, lower profile septal closure devices), intraoperative imaging, or new energy sources (ultrasound tissue erosion for percutaneous closure of an unrestricted ASD in stage I palliation). Electrophysiologists have been able to map and instrument the surface of the heart via a percutaneous approach working in the pericardial space. Better techniques allowing for safer percutal or perventricular delivery of devices through the unopened pericardial space via robotic technology or thoracoscopy should be developed. Extensive use, development, and understanding by surgeons of real-time intraoperative imaging technology by fluoroscopy, 3D echocardiography, intracardiac echocardiography, or MRI is essential. Finally, specially outfitted hybrid suites need to be developed that allow for maximally invasive open-heart surgery and diagnostic imaging on the same table. Such a hybrid OR would potentially allow for a “one-stop shopping” type of management, whereby two traditionally separate interventions (catheterization followed by surgery) would be melded into a single therapeutic session during a single period of anesthesia. The emergence of an interventional/surgical specialist follows logically and needs to be actively pursued by academic teaching institutions. Associated with obvious health care savings, this approach would result in less psychologic trauma for the patients and their families and less potential for human error because the time spent in the hospital is reduced. As is brilliantly exposed in a recent Harvard Business Review article, becoming a “learning leader” is a condition sine qua non to adopting new technologies in high-stress, high-risk, and low-error threshold fields such as pediatric cardiac surgery. In that respect, a paradigm shift needs to occur in congenital heart surgery similar to what vascular surgery went through over the past decade. By keeping up with new technology and embracing endovascular techniques, they have been able to reinvent their field and benefit their patients.

References