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Hybrid procedures can reduce the risk of congenital cardiovascular surgery

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Abstract

Background: Minimally invasive operations and percutaneous interventions are well-accepted options in the treatment of congenital heart defects. However, percutaneous interventions may be associated with an increased risk due to limited vascular access or a very tortuous catheter course. In these cases, combining operative and interventional approaches with direct puncture of the heart or the great vessels may facilitate implantation of even large devices. Furthermore, in some situations, cardiopulmonary bypass or circulatory arrest can be omitted when doing a hybrid procedure. **Patients:** Between January 2000 and April 2007 17 patients were operated in a hybrid fashion. Age ranged from 14 days to 45 years. Operative procedures consisted of implantation of an atrial septal defect occluder via direct puncture of the right atrium ($n = 4$), closure of a ventricular septal defect via direct puncture of the right ventricle ($n = 1$), implantation of isthmus stents via the ascending aorta ($n = 5$), redilation of an isthmus stent ($n = 1$), redilation of a ductal stent ($n = 1$), angioplasty of a pulmonary artery stenosis ($n = 1$), interventional occlusion of an intrahepatic porto-caval shunt ($n = 1$), stent implantation into the right pulmonary artery ($n = 1$) and into the right ventricular outflow tract ($n = 1$) under direct vision as well as atrioseptoplasty combined with a bilateral pulmonary artery banding in one newborn with a single ventricle and very low birth weight ($n = 1$). **Results:** The planned intervention could be performed in all cases under the assistance of intraoperative fluoroscopy, transesophageal or epicardial echocardiography, or under direct vision. In all cases, the primary hemodynamic objectives were achieved. **Conclusion:** In selected patients, the combination of a surgical procedure and a percutaneous intervention may help to reduce both operative and interventional risks. This concept may enable new treatment options, especially in patients with complex congenital heart defects or complex vascular situations.

Keywords: Hybrid; Congenital; Surgery; Intervention

1. Introduction

Although surgery remains the treatment of choice for most congenital cardiac malformations, an increasing number of simple and even complex lesions are nowadays treated interventionally in the catheterization laboratory [1,2]. As experience is growing in both fields, it is becoming apparent that surgical and interventional techniques may not be competing but complementary [3].

The percutaneous approach can be challenging due to patient's low weight or poor vascular access. In addition, the passage of large delivery catheters in small infants may result in rhythm disturbances and hemodynamic compromise [1]. On the other hand, surgery also has its limitations. Generally, intracardiac procedures require the use of cardiopulmonary bypass and sometimes even circulatory arrest, which is associated with adverse effects such as neurologic injury [4—8], and systemic inflammatory response syndrome [9—12]. Furthermore, in most cases, full sternotomy or lateral thoracotomy is required.

We hypothesized that combining surgical and interventional techniques may help to reduce procedural complexity and cardiopulmonary bypass time, thereby decreasing operative risk and improving postoperative outcome. This study was designed to review our early experience with hybrid congenital cardiovascular surgery.

2. Patients and methods

A retrospective study was conducted on 17 patients with congenital heart defects who were treated in our center with hybrid procedures between January 2000 and April 2007.

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Table 1
General indications for hybrid procedures

Indications	Examples
Vascular access	• Very tortuous course of delivery sheaths • Small peripheral vessels vs large sheaths
Better alignment between defect and device	• Large ASD in patients with small left atrium • Bad angle for deployment of VSD-occluders
Avoiding circulatory arrest	• Stent implantation in a hypoplastic arch
Avoiding or shortening of cardiopulmonary bypass in very small children	• Balloon atrioseptoplasty as part of the 'Giessen procedure' in HLHS
Anatomical problem preventing standard surgical procedure	• Poor surgical access in apical VSD • Left anterior descending coronary artery crossing right ventricular outflow tract in tetralogy of Fallot
Interventional procedure during scheduled surgery	• Stent implantation or balloon angioplasty of pulmonary arteries under direct vision

Minimally invasive surgical procedures performed via limited partial lower sternotomies and lateral mini-thoracotomies were not included in this study. The indications for suggesting a hybrid approach in these selected patients are summarized in Table 1. Each single procedure was discussed with the patients or their guardians on an individual basis. Informed consent for both surgery and intervention was obtained for all procedures. All procedures were performed by two cardiac surgeons (CS and BE) and one pediatric cardiologist (JB).

Median age at time of the hybrid procedure was 0.58 years, ranging from 14 days to 45 years. Mean body weight was 6.15 kg, ranging from 2.0 to 98 kg. There were 7 female and 10 male patients. Underlying diagnoses, age at time of procedure, and procedures performed are summarized in Table 2.

The Aristotle Basic Score [13] was used to estimate the complexity of congenital heart surgery in a given patient. It was calculated twice for each patient: one calculation considered the procedure, which was actually performed (i.e. actual score), the second calculation was based on the assumption that the whole procedure would have been performed surgically (i.e. theoretical score) (Table 2).

Furthermore, expected mortality of congenital heart surgery according to the EACTS congenital database (http://www.eactscongenitaldb.org — Int. Nomenclature 2005: Mortality vs Procedure) was calculated twice for each patient the same way: actual mortality risk vs theoretical mortality risk (Table 2).

3. Technical aspects

3.1. Atrial septal defect (ASD) closure

A subxiphoid access was used for closure of ASDs in patients with a vena azygos continuity or a small left atrium, which precluded proper deployment of an interventional device. It was done via a skin incision of 1.5—3 cm length, dividing just the cartilage part of the xiphoid without splitting the sternum (Fig. 1a). After pericardial incision, the delivery system was shortened, and inserted into the right atrium via direct puncture through a double Teflon-armed purse string suture. Implantation of the atrial septal occluder (Amplatzer, AGA Medical Corp, Golden Valley, Minnesota, USA) was performed in all patients under the guidance of transesophageal echocardiography alone (Fig. 1b—d).

3.2. Ventricular septal defect (VSD) closure

In one patient with a residual VSD, it was not possible to close the defect by percutaneous intervention. Therefore, implantation of the device was carried out in a hybrid procedure using a median sternotomy. Dissection of adhesions was minimal; just the anterior wall of the right ventricle was exposed. A shortened sheath was inserted through a purse string suture on the anterior wall of the right ventricle across the residual VSD. After administration of 100 I.E. heparin per kg body weight, a 7 mm Amplatzer septal occluder (AGA Medical Corp, Golden Valley, Minnesota, USA) was implanted under guidance of transesophageal echocardiography alone (Fig. 2a—d). Due to its lower profile, the ASD occluder fitted much better into the patch defect than a VSD occluder.

3.3. Stenting of coarctation

Recoarctation may be treated by angioplasty or stent implantation. In small children, these stents should be redilatable to the size of an adult aorta. However, such stents require large delivery sheaths, which cannot be used retrogradely from small femoral arteries. Therefore, we used an antegrade stent implantation technique in such patients who required an additional surgical procedure, e.g. Glenn operation. The implantation was done following the surgical procedure after the patient was weaned from cardiopulmonary bypass (Fig. 3a,b). The arterial cannula was removed from the ascending aorta, and a 10F delivery system was introduced through the same incision. Heparin was partially reversed in order to keep the activated clotting time above 200 s. A bare metal stent (CP-stent 8Z16, PFM, Cologne, Germany) was introduced through the sheath, and placed under guidance of fluoroscopy. After a final position check, the sheath was removed, heparin was fully antagonized, and the operation was completed as usual.

3.4. Stent implantation into pulmonary artery

Stent implantation into the pulmonary artery was done in one case of tetralogy of Fallot to avoid transverse dissection of the ascending aorta for patch plasty of the right pulmonary artery. This stent (CP-stent 8Z16, PFM, Cologne, Germany) was placed into the right pulmonary artery behind the ascending aorta under direct vision.

Table 2
Patients who underwent hybrid congenital cardiovascular procedures, technical guidance used during the operation, and indication for using the hybrid approach

#	Age	Height (cm)	Weight (kg)	Diagnosis	Hybrid procedure	Technical guidance	Indication	Outcome	ABS w hybrid	ABS w/o hybrid	MR w hybrid	MR w/o hybrid
1	5 mo	56	3.8	ASD, small body weight, heart failure	ASD Amplatzer	TEE	No CPB, PVA, NS		3	1.5	0.31	0
2	1 y	75	8.8	ASD, azygos continuity	ASD Amplatzer	TEE	No CPB, PVA, NS		3	1.5	0.31	0
3	45 y	152	98	ASD, large body mass index	ASD Amplatzer	TEE	No CPB, NS		3	1.5	0.31	0
4	23 y	183	78	Ebstein's anomaly, ASD	ASD Amplatzer	TEE	No CPB, NS		3	1.5	0.31	0
5	22 y	161	61	Residual shunt after VSD closure	VSD Amplatzer	TEE	No CPB, NS		6	1.5	1.56	0
6	0.5 mo	49	2.0	HLHS, severe PFO obstruction, low birth weight	Bilateral PA banding and atrioseptoplasty	EE	No CPB, NS	Deceased 2 weeks p.o.	6	6	25.6	8.82
7	3 mo	57	4.0	HLHS, S/P Norwood, re-CoA, PA-stenosis	Glenn operation and stenting of re-CoA & PA-angioplasty	F, TEE	Shorter CPB, no CA		8	7	8.82	5.16
8	6 mo	65	6.5	HLHS, S/P Norwood, re-CoA	Glenn operation and stenting of re-CoA	F	Shorter CPB, no CA		8	7	8.82	5.16
9	5 mo	63	5.8	HLHS, S/P Norwood, re-CoA	Glenn operation and stenting of re-CoA	F	Shorter CPB, no CA		8	7	8.82	5.16
10	9 mo	70	5.7	HLHS, azygos continuity, S/P Norwood, re-CoA	Kawashima operation and stenting of re-CoA	F	Shorter CPB, no CA		8	7	8.82	5.16
11	7 mo	61	4.7	VSD, hypoplastic arch, S/P PA-banding & end-to-end anastomosis, re-CoA	VSD closure and stenting of re-CoA	F	Shorter CPB, no CA		10	6	8.82	1.56
12	7 mo	63	5.0	VSD, very small LV, S/P stent implantation in CoA	VSD patch closure and dilation of stent in CoA	F	Shorter CPB, no CA		10	6	8.82	1.56
13	7 mo	65	5.3	Critical AoS, MS, small LV, PDA dependent systemic circulation	Bilateral PA banding and dilation of stent in PDA	F	Shorter CPB, no CA		6	6	8.82	8.82
14	2 mo	53	2.9	Imbalanced AVSD, pulmonary atresia, right isomerism, TAPVC into portal vein, S/P intrahepatic stent implantation to create a porto-caval shunt	TAPVC correction, MBTS, and interventional occlusion of intrahepatic stent	F	Shorter CPB, shorter CA	Deceased 1 day p.o.	9	9	11.8	11.8
15	4 mo	61	6.6	HLHS, S/P Norwood, LPA-stenosis	Glenn operation and LPA-angioplasty	DV	Shorter CPB		7.8	7	7.38	5.16
16	8 mo	67	6.5	ToF, RPA stenosis	ToF repair and stenting of RPA	DV	Shorter CPB		8	8	7.38	3.84
17	13 mo	74	8.2	ToF, LAD crossing RVOT	ToF repair and stenting of RVOT	DV	Reduced complexity		8	8	3.84	2.41

mo: months; y: years; w: with; w/o: without; ABS: Aristotle Basic Score; AoS: aortic stenosis; ASD: atrial septal defect; CoA: coarctation of the aorta; CPB: cardiopulmonary bypass; CR: cosmetic result; DV: direct vision; EE: epicardial echocardiography; F: fluoroscopy; HLHS: hypoplastic left heart syndrome; LAD: left anterior descending artery; LV: left ventricle; MBTS: modified Blalock—Taussig shunt; MR: mortality risk (EACTS database); MS: mitral stenosis; NS: no sternotomy; PA: pulmonary artery; PDA: persistent ductus arteriosus; PVA: poor vascular access; RPA: right pulmonary artery; RVOT: right ventricular outflow tract; TAPVC: totally anomalous pulmonary venous connection; TEE: transesophageal echocardiography; ToF: tetralogy of Fallot; VSD: ventricular septal defect.

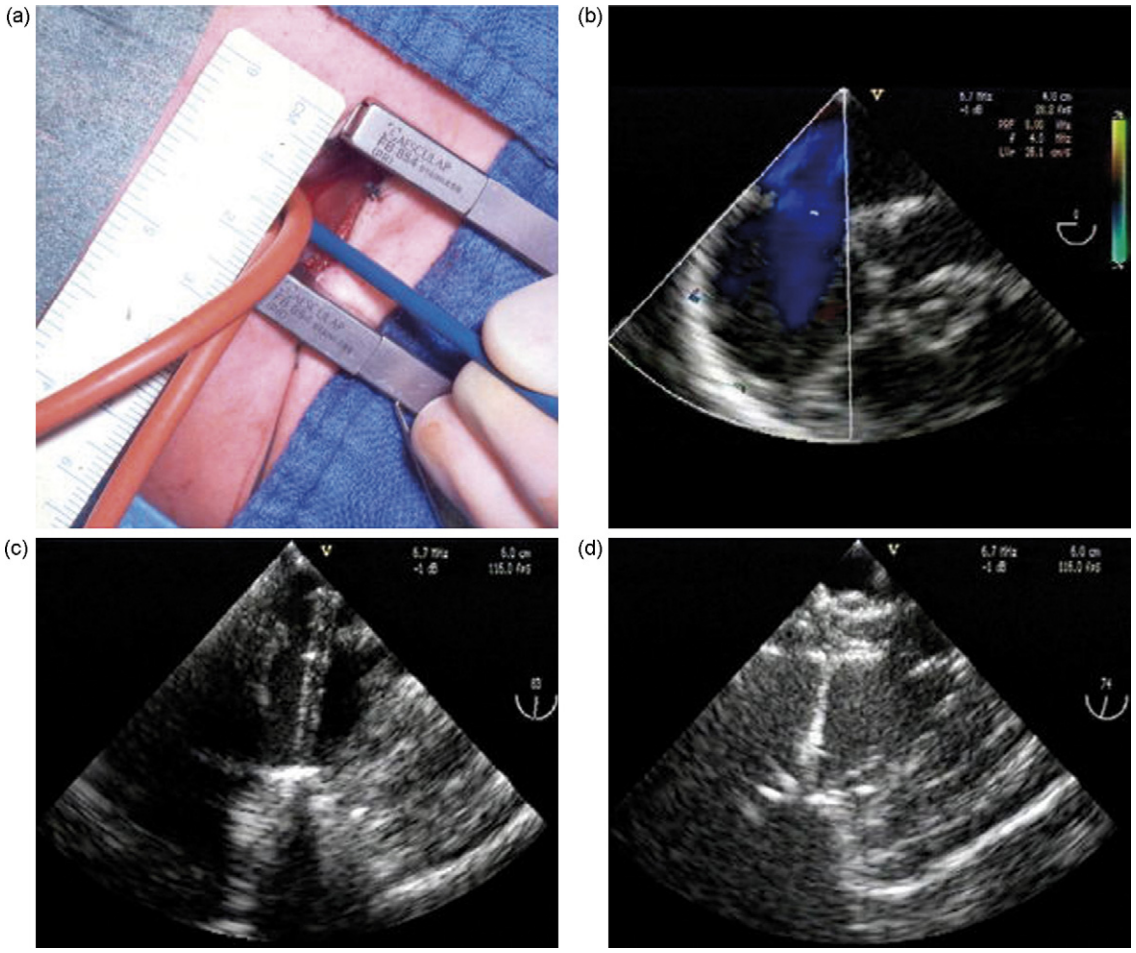

Fig. 1. (a) Subxiphoid skin incision (2 cm) to put a purse string suture on the anterior wall of the right atrium. (b) Transesophageal echocardiography of the atrial septal defect. (c) Transesophageal echocardiographic view of the delivery sheath (8F) with its tip in the left atrium after direct puncture of the right atrium. (d) Expanded occluder (10 mm ASO; AGA Medical, Plymouth, MN, USA) still on the delivery cable just before release.

3.5. Stent implantation into right ventricular outflow tract

In this patient, the right ventricular outflow tract could not be incised in the usual fashion, because it was crossed by a large additional LAD. Therefore, a stent (CP-stent 8Z16, PFM, Cologne, Germany) was implanted into the right ventricular outflow tract under direct vision.

3.6. Atrioseptoplasty

In one patient with hypoplastic left heart syndrome, low birth weight (2.0 kg) and restrictive PFO, an atrioseptoplasty was performed via direct puncture of the right atrium under guidance of epicardial echocardiography after a median sternotomy (Fig. 4a—c). Thereafter, a bilateral banding of the pulmonary artery was performed as a first step of the so-called 'Giessen-procedure' [14]. This baby died unexpectedly 14 days after the operation and 2 days after extubation, most probably due to intractable acute failure of the right ventricle. Echocardiography performed 1 day before death showed a sufficiently enlarged PFO and bilateral stenotic pulmonary arteries at the banding sites. However, the non-functioning left ventricle seemed to slightly compress the right ventricle. This compression might have increased later and subsequently severely disturbed the function of the right ventricle, which was the systemic ventricle in this condition.

3.7. Interventional closure of an intrahepatic stent

The procedure was carried out on cardiopulmonary bypass while cooling down the patient for deep hypothermic circulatory arrest to correct total anomalous pulmonary venous connection (TAPVC). The patient also suffered from low birth weight, imbalanced AVSD, pulmonary atresia and right isomerism. Six weeks earlier at a body weight of 1.200 g, a stent had been implanted in order to create a porto-caval shunt for treatment of acute pulmonary edema. After correction of TAPVC, creation of a modified Blalock—Taussig shunt and closure of the porto-caval shunt by a 6 mm Amplatzer — vascular plug (AGA Medical Corp, Golden Valley, Minnesota, USA), this patient could not be weaned from cardiopulmonary bypass and stayed on ECMO for 24 h. In spite of using catecholamines and vasodilators myocardial function was heavily depressed and no reason could be elucidated. An unrestricted pulmonary venous return, an intact Blalock—Taussig shunt and a complete occlusion of the porto-caval shunt were verified by color

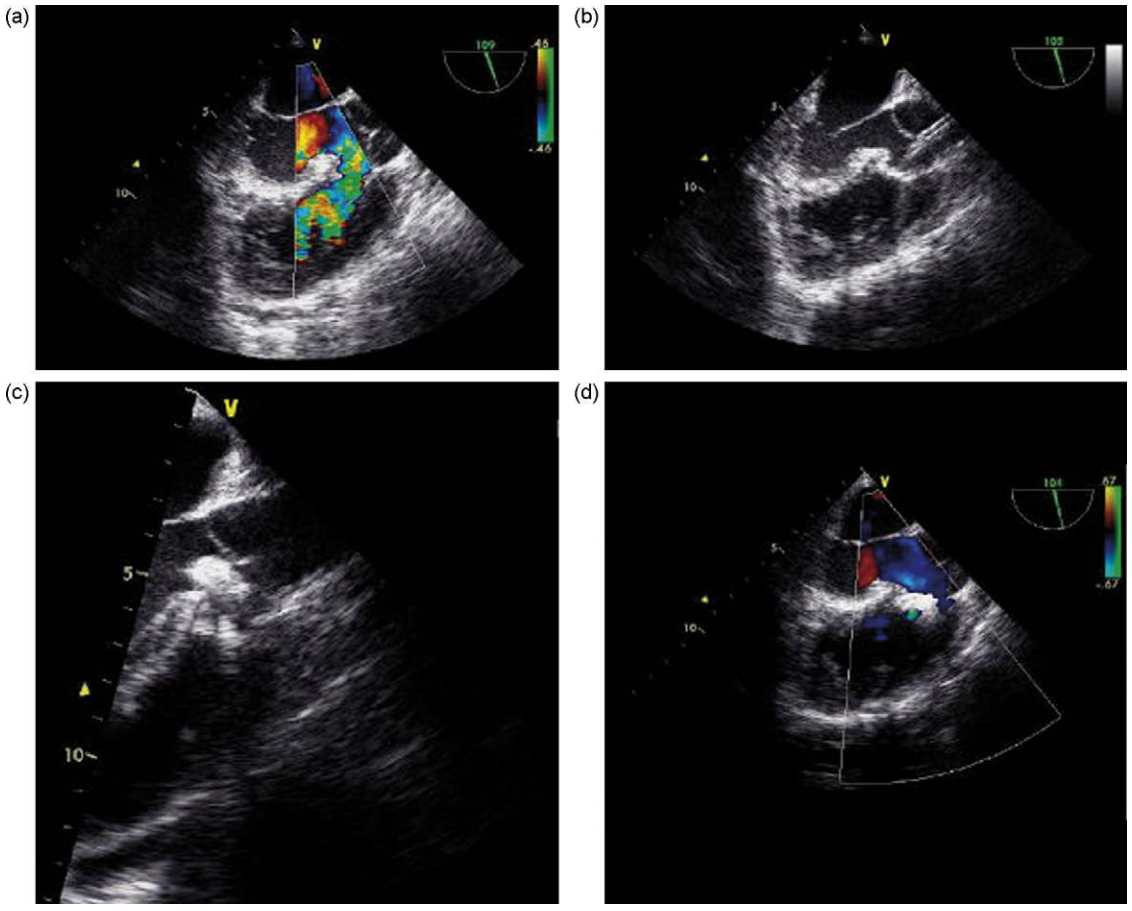

Fig. 2. (a) Transesophageal echocardiographic view of a residual VSD 1.5 years after patch closure. (b) 7F long sheath within the ascending aorta crossing the patch defect after direct puncture of the right ventricle. (c) Transesophageal echocardiography shows the expanded distal part of the occluder (7 mm ASO; AGA Medical, Plymouth, MN, USA) just below the aortic valve. (d) Complete closure of the residual VSD after deployment of the device.

flow Doppler echocardiography and angiography. During ECMO the baby developed multi-organ failure as well as systemic inflammatory response syndrome and died 24 h later. Since the mortality in patients with isomerism-syndromes is extremely high [15], some other and currently unknown factors might have been involved in this fatal course.

4. Results

Eight-eight percent (15/17) of the patients survived their hospital stay. One child (TAPVC repair) died on the first postoperative day due to multi-organ failure. The second death occurred 2 weeks after the operation after the child was weaned from ventilator due to heart failure. There were no device related complications. Mean stay on ICU was 15 days ranging from 0 to 56 days; mean time to discharge was 18 days, ranging from 1 to 56 days.

In all cases the planned interventions could be performed under the assistance of intraoperative fluoroscopy, transesophageal echocardiography, epicardial echocardiography or under direct vision (Table 2). Furthermore, in all cases, the primary hemodynamic objectives were achieved.

The Aristotle Basic Score dropped significantly ($p = 0.001$) from 6.75 ± 2.43 (theoretical score without intervention) to 5.38 ± 2.70 (actual score with intervention). The expected mortality according to the EACTS database decreased significantly ($p = 0.005$) from $7.09 \pm 6.18\%$ (theoretical mortality risk without intervention) to $3.80 \pm 3.60\%$ (actual mortality risk with intervention) ($p = 0.005$).

Until now, stent redilation was performed without any problems in three patients. In all cases, stents could be opened up to the appropriate diameter (8—14 mm; Fig. 5a,b) by means of a high-pressure balloon (Powerflex, Cordis, Norderstedt, Germany).

5. Discussion

This study summarizes a single center experience with hybrid congenital cardiovascular procedures, where surgical and interventional approaches were combined in order to decrease surgical and/or interventional trauma.

In general, interventional approaches to treat congenital malformations seem to be preferred over surgical procedures. However, under certain circumstances the intervention may be associated with an increased risk. Sometimes it is even impossible to perform the intervention, e.g. due to patient's low weight or vascular access issues [5]. In these cases, a hybrid procedure may be considered. The surgeon provides optimal access, and the cardiologist performs the

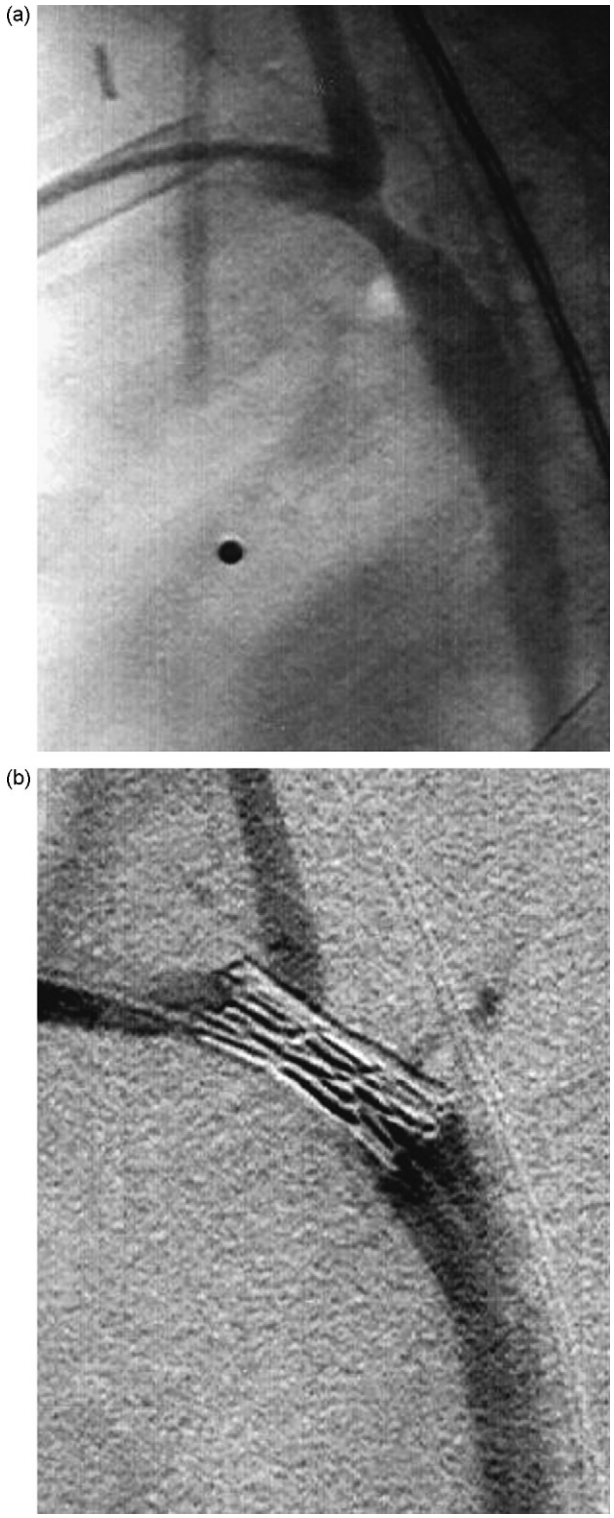

Fig. 3. (a) Intra-operative angiography of the aortic isthmus at the time of surgical VSD-closure delineating a recoarctation. (b) Intraoperative Digital Subtraction Angiography after implantation of a stent (CP 8Z16; PFM, Cologne, Germany).

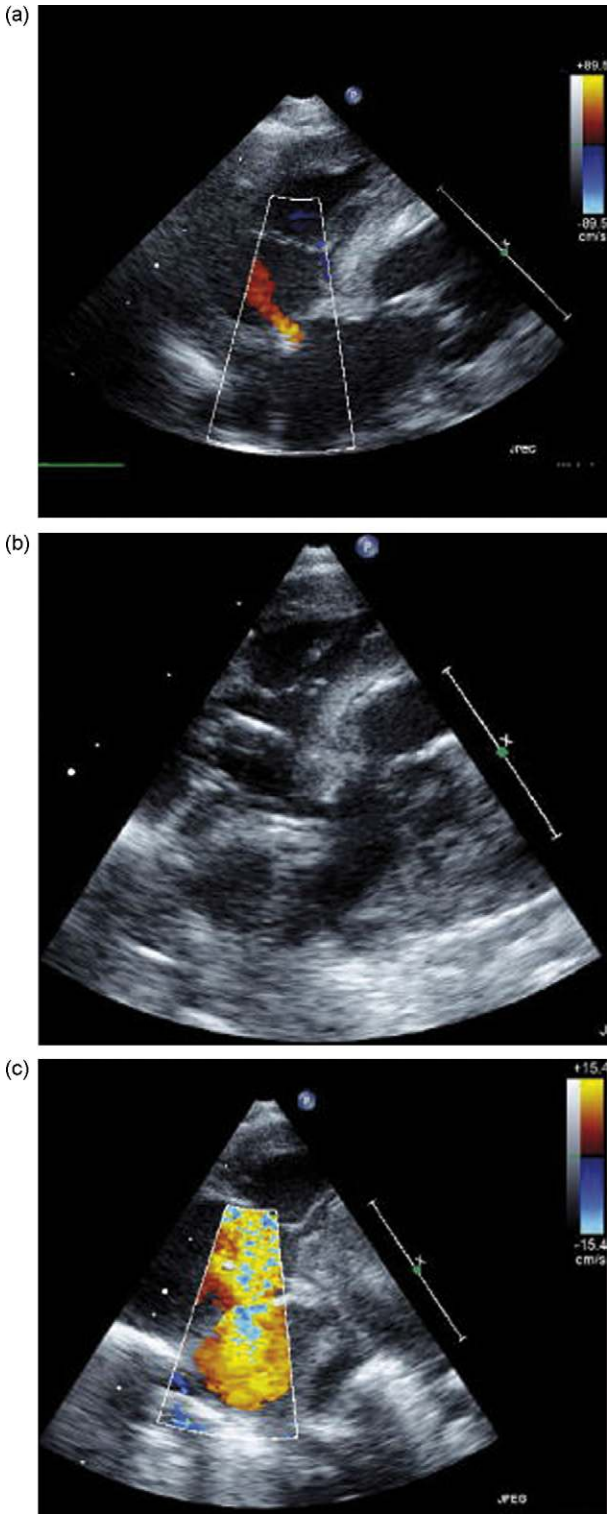

Fig. 4. Epicardial echocardiography was used to direct atrioseptoplasty in a 2.0 kg newborn. (a) Restrictive PFO with an inter-atrial peak gradient of 6.7 mmHg. (b) Dilation of the PFO with a 10 mm balloon after direct puncture of the right atrium. (c) Result of the procedure leaving a residual inter-atrial peak gradient of 1.4 mmHg.

intervention. This collaborative approach may help to reduce the procedural risk for both surgery and intervention.

Currently, closure of secundum type ASDs is generally done via interventional implantation of an umbrella type device [16—18]. Contraindications for the use of a device are patient's low weight (below 5 kg) or a missing rim, which is needed for the proper fixation of the device. However, under certain circumstances even defects that are suitable for

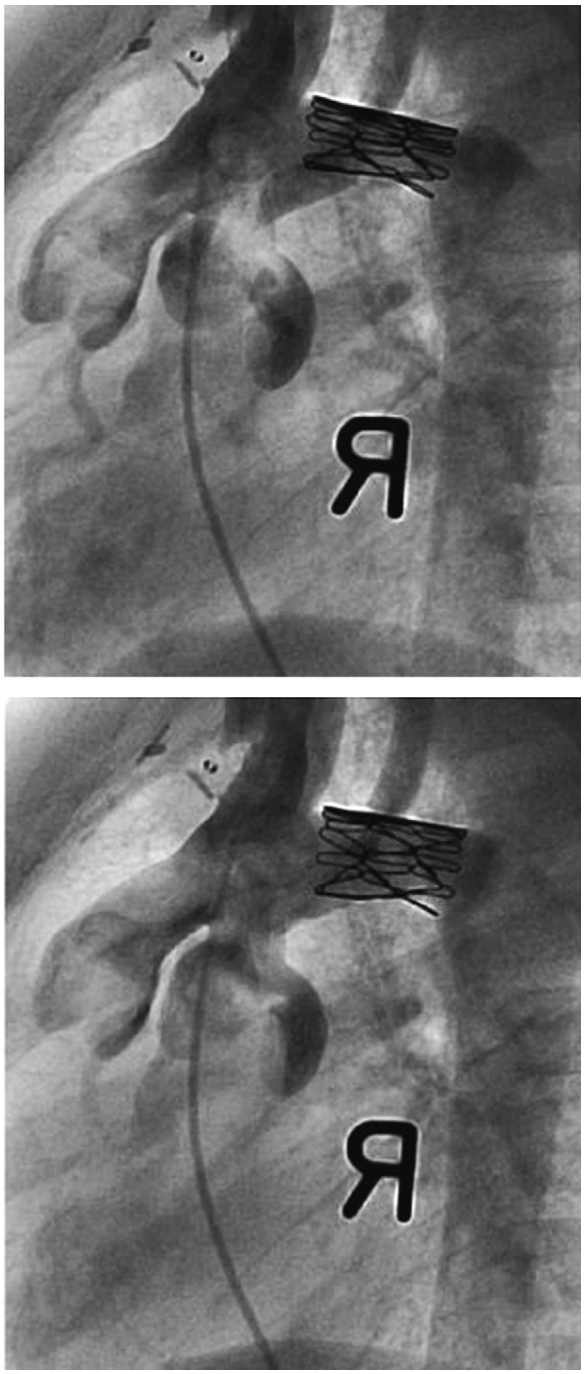

Fig. 5. Angiography before (a) and after (b) redilation of a stent (CP 8Z16; PFM, Cologne, Germany) within the aortic isthmus 18 months after its implantation by hybrid pediatric cardiac surgery.

interventional implantation can be very difficult or even impossible to close with a device.

In our series, there was one child presenting with an ASD in combination with a vena azygos continuity. In this patient, the normal pathway via inferior vena cava did not exist. The anatomical options to access the heart via azygos vein and superior vena cava or via jugular vein and superior vena cava were not suitable as it turned out to be too tortuous for the device to navigate. Another published option to address this issue is direct puncture of a liver vein [19—22]. However, this so-called transhepatic access is associated with an increased risk of bleeding, as the delivery system is very large (10F). In our patient direct puncture of the right atrium seemed to be the least invasive approach.

During the first procedures it became apparent, that the above-described method had another advantage, which was not anticipated before. As the angle of the introducer catheter is almost perpendicular to the atrial septum, it was very easy to implant devices in patients with very small left atriums. In one patient with Ebstein's anomaly and atrial septal defect, the implantation of an ASD occluder failed twice, as it was not possible to rotate the device in the left atrium as required for proper positioning in the ASD.

Another important concern of percutaneous device closure is exposure to radiation [23]. In our series, all implantations of ASD occluders did not require the use of fluoroscopy, although in the first cases we were prepared to utilize it.

Although minimally invasive surgical approaches for ASD closure, as limited sternotomy or thoracotomy show acceptable cosmetic results, there seems to be an easy rule: smaller is better. The main determinant for the size of the skin incision is the space that is required for cannulation for cardiopulmonary bypass. The ascending aorta as well as both vena cava have to be cannulated. When doing a procedure without cardiopulmonary bypass, the size of the skin incision can be considerably decreased. The smallest skin incision we used was just 1.5 cm, which is far smaller than everything that would be required for a standard (minimally invasive on-pump) surgical approach.

Hybrid implantation of a device into a residual VSD was performed in this study because the Amplatzer device could not be rotated in the left ventricular outflow tract, when approached via the femoral vein. When implanting the device via the anterior right ventricular wall, the angle to the VSD was more or less perpendicular. This significantly facilitated the exact positioning of the left sided umbrella. Compared to the standard surgical approach, separation of adhesions was reduced considerably, as only the anterior wall of the right ventricle was required to perform this procedure.

In five children with hypoplastic left heart syndrome, where bovine pericardium was used to reconstruct the aortic arch during the Norwood operation, a recoarctation was treated with antegrade stent implantation into the aortic isthmus at the time of the scheduled Glenn operation. This complication of recoarctation was rarely seen in our center when performing the aortic arch reconstruction using pulmonary homografts. Due to the lack of suitable homografts, glutaraldehyde treated bovine pericardium was used in several cases to enlarge the aortic arch. Although this material has beneficial physiologic characteristics, the major disadvantage is the tendency to shrink, leading to recoarctation. The surgical relief of recoarctation in this setting is very difficult because of extreme formation of adhesions and the stenotic area lying behind the reconstructed aortic arch. Instead, we looked for an alternative treatment option. The antegrade pathway chosen in these patients allowed the implantation of extremely large stents into small children. The stents we used can be dilated up to 25 mm in the future. This should be adequate even for adult aortas.

Looking at changes in risk is very difficult; as there are no published data concerning combined surgical procedures, e.g. bidirectional Glenn operation and surgical relief of recoarctation. We tried to estimate the risk of the operations with two different calculations. The Aristotle Basis Score takes in account the complexity of cardiac operations; the EACTS database gives actual information about in-hospital mortality for certain operations. When doing a part of the operation interventionally, the rest of the operation becomes less complex, at least for the surgeon. However, we are aware that this method does not take into account how far the intervention itself increases the risk or complexity of the procedure. However, we think, that these calculations may help to make a rough estimate. This estimate met our expectations, that the overall risk of the hybrid procedure was reduced compared to the risk of the complete surgical option. The fact that this risk reduction was statistically significant in both calculations (Artistotle Basic Score and EACTS Database Hospital Mortality) was a surprise.

6. Study limitations

The previously described procedures were performed in highly selected cases. During the same time period about 500 surgical procedures and about 300 interventions were done in our center. The selection was based on the surgeons' and cardiologist's preference. Another limitation is the retrospective nature of the study.

7. Conclusion

Close collaboration between pediatric cardiac surgeons and pediatric cardiologists is essential in the modern management of congenital heart defects. The hybrid approaches described in our study are examples how this can be accomplished. Hybrid procedures may help to reduce procedural risks and improve cosmetic results. Using this technique some procedures might be performed which could not be carried out by surgeons or cardiologists alone. The above-described patients are only a very small proportion of patients requiring surgery or intervention. However, with increasing experience, these procedures can be performed in even more cases in order to further reduce morbidity and eventually improve outcome.

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