Current Cardiology Reviews, 2016, *12*, 258-269

REVIEW ARTICLE

Therapeutic Utilities of Pediatric Cardiac Catheterization

Giannis A. Moustafa[1], Argyrios Kolokythas[1], Konstantinos Charitakis[2,3] and Dimitrios V. Avgerinos[2,3]*

[1]*Society of Junior Doctors, Surgery Working Group, Athens, Greece;* [2]*Athens Heart Institute, Athens, Greece;* [3]*Department of Cardiothoracic Surgery, New York Presbyterian - Weill Cornell Medical Center, New York, USA*

ARTICLE HISTORY

Received: May 5, 2015
Revised: December 17, 2015
Accepted: December 22, 2015

DOI: 10.2174/1573403X12666160301121253

Abstract: In an era when less invasive techniques are favored, therapeutic cardiac catheterization constantly evolves and widens its spectrum of usage in the pediatric population. The advent of sophisticated devices and well-designed equipment has made the management of many congenital cardiac lesions more efficient and safer, while providing more comfort to the patient. Nowadays, a large variety of heart diseases are managed with transcatheter techniques, such as patent foramen ovale, atrial and ventricular septal defects, valve stenosis, patent ductus arteriosus, aortic coarctation, pulmonary artery and vein stenosis and arteriovenous malformations. Moreover, hybrid procedures and catheter ablation have opened new paths in the treatment of complex cardiac lesions and arrhythmias, respectively. In this article, the main therapeutic utilities of cardiac catheterization in children are discussed.

D.V. Avgerinos

Keywords: Cardiac, catheterization, children, heart, interventions, pediatric, therapeutic.

INTRODUCTION

Cardiac surgery has played a fundamental role in the management of congenital heart disease (CHD). However, during the last decades, the advance of transcatheter techniques has led to the substitution of many traditional surgical procedures, due to favorable outcomes, better safety and more comfort for the patient, offered by the former. In addition, the development of special devices and equipment gave the opportunity for more interventions and, in many cases, established therapeutic catheterization as the gold standard of treatment. Nowadays, many CHDs are effectively managed with transcatheter techniques. Patent foramen ovale, atrial and ventricular septal defects, valve stenosis, patent ductus arteriosus, aortic coarctation, pulmonary artery and vein stenosis and arteriovenous malformations are some examples, routinely treated with catheterization in the pediatric population. Purpose of this review is to highlight the main utilities of cardiac catheterization as a therapeutic tool in the pediatric patient, including a brief report on the novel procedures of transcatheter valve replacement and hybrid interventions. A referral to the whole technique's complications is also made at the end of the article.

*Address correspondence to this author at the Department of Cardiothoracic Surgery, Athens Medical Center & Center for Percutaneous Valves and Aortic Diseases, 5-7 Distomou Street, 15125, Marousi, Attica, Greece; E-mail: davgerinos@gmail.com

PATENT FORAMEN OVALE (PFO)

Under conditions that increase right atrial pressure, the septum primum flap is pushed away from the septum secundum, allowing blood to flow from the right to the left atrium and PFO generates pathology.

"Cryptogenic stoke" (CS) is linked to PFO, [1-4] which is seen in 20-25% of the general population, but approximately 50% of CS patients. Closure or anticoagulation therapy in PFO patients who experienced stroke or transient ischemic attack (TIA) contributes to secondary stroke prevention, compared to no treatment, but there is controversy on whether closure offers better results for post-CS patients, compared to medical treatment. Nonrandomized studies showed annual recurrence rate of 0-5% for stroke or TIA in patients after device closure [5-7], and 3.8-12% for those under anticoagulants [8-11]. However, randomized controlled trials (RCTs) failed to highlight substantial benefit of percutaneous closure. CLOSURE-I [12] compared recurrence rates of stroke or TIA with device closure (STARFlex device - NMT Medical, Inc.) and medical treatment, showing no superiority of the former. Yet, the STARFlex is not the best choice [13] and CLOSURE-I was criticized regarding patient selection. PC trial compared the Amplatzer PFO Occluder (St. Jude Medical, Inc.) with antithrombotic therapy showing similar results [14]. RESPECT [15] did not demonstrate device closure superiority in the primary intention-to-treat analysis, but emerged positive results in the prespecified secondary per-protocol and as-treated analyses. RE-

1875-6557/16 $58.00+.00

DUCE (NCT00738894), examining the efficacy of the Helex Septal Occluder (W.L. Gore & Associates), is ongoing.

Migraine is also associated with PFO [16]. Observational data suggest some improvement with PFO closure [16-19], while from RCTs, MIST [20] failed to yield positive results and PRIMA (NCT00505570) and PREMIUM (NCT00355056), are ongoing.

PFO closure is considered a safe procedure and is performed off-label, depending on the therapist's experience and the institution's policy. Major complication rate has been estimated to be 0.2%-1.5% for hemorrhage requiring transfusion, cardiac tamponade, fatal pulmonary emboli, and death [21]. Minor complication risks, i.e., atrial arrhythmias, device arm fractures, device embolization and thrombosis, and femoral hematomas occur at 7.9%-11.5% of patients [21]. Atrial fibrillation occurs more frequently in patients who received larger devices [22].

High-risk for stroke, frequent right-to-left shunting and cyanosis episodes in the context of a noncompliant right ventricle and orthodeoxia-platypnea syndrome are reasonable indications for PFO closure [21].

ATRIAL SEPTAL DEFECT (ASD)

ASD accounts for about 8.5% of all CHDs. Although small defects (<8mm) are commonly found soon after birth, the majority closes spontaneously within the first year. Approximately 90% of ASDs are secundum ASDs, while the 10% includes primum, sinus venosus and unroofed coronary sinus defects. The first attempt for percutaneous ASD closure was in 1976 [23], but FDA approved the Amplatzer Septal Occluder (ASO, St. Jude Medical, Inc.) only in 2001 (Fig. **1**). ASO is a double-disc, self-expandable device composed of a Nitinol wire mesh. The discs are connected with a waist and polyester fabric inserts are sewn into the discs and the waist to facilitate closure. Before release of the delivery cable, the device can be easily repositioned. The Helex Septal Occluder (HSO) and the Amplatzer Multi-fenestrated Septal Occluder (AMFSO - St. Jude Medical, Inc.) or "Cribriform" Occluder, followed (Fig. **1**). The HSO consists of a single nitinol strand connected to a piece of an expanded polytetrafluoroethylene membrane, while the AMFSO resembles the ASO. ASO is most widely used and can close ASDs up to 38mm. HSO is mostly used for small- to moderate-sized defects (<2cm), and AFMSO for multi-fenestrated ASDs. Catheter-based closure is routinely performed under intracardiac or transesophageal ultrasound. Percutaneous ASD closure seems to be equally successful to surgical repair with 98% success, and lower complications rates, shorter operative and hospitalization time and faster recovery [24-26]. Very large ASDs (>38mm), troublesome cases with insufficient defect rims and non-secundum types of ASD are amenable to surgical repair. Dyspnea, fatigue, paradoxical embolism, tachyarrhythmias and right heart failure are possible manifestations of untreated ASDs. Complications of percutaneous ASD repair include device migration and malposition, cardiac perforation resulting in tamponade, and atrioventricular block. A multicenter study of 442 children showed 7.2% overall complication rate with 1.6% considered to be major, due to device embolism, cardiac arrhythmia requiring major treatment, marker band embolization, and cerebral embolism with extremity numbness [24].

Fig. (1). Amplatzer Septal Occluder (top), Amplatzer Multi-fenestrated Septal Occluder (bottom).

VENTRICULAR SEPTAL DEFECT (VSD)

VSD is the commonest CHD of childhood, but its spontaneous closure decreases its prevalence in adults. VSD's subtype are: perimembranous (pmVSD-80%), muscular (mVSD-10%), inlet (5%), supractristal (<5% in non-Asians)

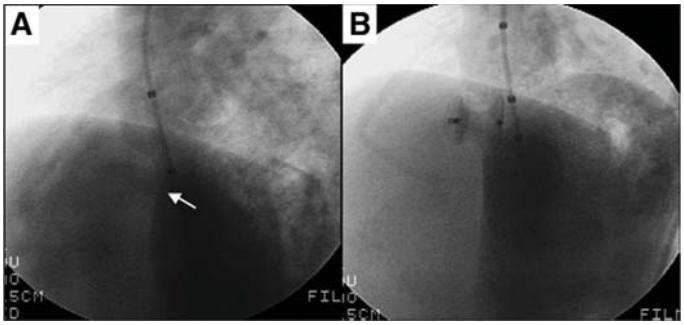

Fig. (2). (**A**) Left ventricle angiogram in the long axial oblique view (long axial oblique: 50°, cranial: 15°) shows a high mVSD (arrow) with about 6mm diameter. (**B**) Same capture after implantation of an 8-mm Amplatzer Muscular VSD Occluder; successful closure. (Hijazi ZM, Awad SM. Pediatric cardiac interventions. JACC Cardiovascular Interventions 2008; 1(6): 603-11).

and rarely multiple VSDs ("Swiss-cheese"). Currently, percutaneous VSD closure is performed only on mVSD. Usually, small VSDs are asymptomatic with excellent prognosis needing no treatment. Although percutaneous approach has been succesfully tested on pmVSD [27], most studies show increased postoperative AV-block incidence [28, 29] and surgical closure is the treatment of choice in moderate or large pmVSD. According to the American Heart Association Indications for Cardiac Catheterization and Intervention in Pediatric Cardiac Disease, percutaneous VSD device closure is indicated only for infants >5kg and children and adolescents with hemodynamically significant defect (left heart chambers overload or pulmonary-blood-flow:systemic-blood-flow >2:1) [30]. The first labelled device was the Amplatzer Muscular VSD Occluder (St. Jude Medical, Inc.) (Fig. **2**), approved by the FDA in 2007, after successful use in transcatheter mVSD closure [31]. It consists of a self-expandable, double-disc implant made of wire mesh and Dacron polyester fabric and a delivery system, which facilitates transport of the implant to the defect. In the prospective study of Hozler *et al*. following patients with mVSDs after device closure, 45% of patients suffered at least one procedure-related complication, with conduction anomalies, hypotension/cardiac arrest, hematoma/pseudoaneurysm, cerebrovascular accident, and device embolization being the most common [31]. Neonates and smaller infants with hemodynamically significant mVSD are amenable to surgical or better hybrid procedure [30], with which cardiopulmonary bypass is avoided and may also be helpful in multiple VSDs [32].

ATRIAL SEPTOSTOMY AND TRANSSEPTAL APPROACH

Balloon atrial septostomy (BAS) was the first interventional cardiac transcatheter technique performed [33]. Through femoral or umbilical vein a balloon is guided to the left atrium via the right atrium and the foramen ovale. After confirming the position by fluoroscopy or echocardiography, an abrupt pull tears the septum magnifying the interatrial communication. Pressure gradient is checked across the defect and the procedure is ongoing until atrial pressures are equalize. Mostly used catheters are the Miller (Edwards Lifesciences) and the NuMed (NuMed, Inc.). In children >1 month and adults the septum is thick, and the foramen ovale closed, thus BAS cannot be performed and atrial septostomy (BlAS) is the gold standard, creating a defect via a blade, which is then enlarge by a static balloon septostomy or BAS. Alternatively, a Brockenbrough needle (Medtronic, Inc.) or radiofrequency may be used to puncture the septum [30, 34]. Stents can, ultimately, be deployed for more solid results. Primary indication for BAS is newborns and infants with transposition of the great arteries and PFO in order to ensure a few days of survival, since PFO's enlargement offers hemodynamic stabilization and prolonging survival until the surgery. Hypoplastic left heart syndrome with intact interatrial septum is another indication, again as a life-saving procedure, relieving left atrial hypertension and increasing oxygen content in the systemic circulation. Other indications are patients with right-heart obstructive lesions (e.g. tricuspid atresia, pulmonary valve stenosis/atresia) with intact interatrial septum and patients with severe pulmonary hypertension as a last resort therapeutic option [35, 36]. Finally, many left-heart interventions are routinely managed with the transseptal technique when the specialist deems it favorable or when retrograde left-heart access is contraindicated [30]. BAS and the other transseptal techniques are not entirely safe; cardiac perforation, arrhythmias, air embolization and valve injury are some of the complications.

AORTIC STENOSIS

Congenital aortic stenosis is characterized by thickening of the valve leaflets and variable degree of commissural fusion, that hinders blood ejection to the aorta, causing left-heart obstruction. Transcatheter techniques have a palliative nature, aiming to reserve the valve and delay surgery or replacement until after adolescence. Results are not permanent, since restenosis occurs often [37]. Aortic balloon valvuloplasty is a percutaneous procedure, involving the inflation of a balloon at the aortic annulus with intention to rip the commissural fusions and fix the obstruction. Concomitant right ventricular pacing stabilizes the balloon by decreasing left ventricular systolic pressure [38]. Before the procedure a diagnostic catheterization is necessary to collect useful data (pressure gradient across the valve, annular diameter, coexisting regurgitation). Indications include neonates with critical stenosis without regurgitation, irrespective of the pressure gradient, infants and children with stenosis without regurgitation, with resting peak-to-peak systolic gradient >50mmHg and infants and children with stenosis and no regurgitation with resting peak-to-peak systolic gradient >40mmHg and concurrent signs of ischemia (angina, ST changes) or syncope [30]. Annular diameter is important for determining the balloon size (ideally 90-100%) [39]. Smaller sizes lead to suboptimal results with residual obstruction and higher restenosis risk, whereas larger predispose to postprocedural regurgitation [37, 39, 40]. Vascular injury at the injection site, thromboembolic stroke, mitral valve injury, and myocardial perforation in newborns are other potential adverse events [30]. Gradient reduction at least 50% with no induced regurgitation achieves optimal results. Aortic balloon valvuloplasty can be performed by retrograde arterial or antegrade venous access through the interatrial septum. Fratz *et al*. followed 188 pediatric patients (group <1 and group ≥1 month of age) that had undergone aortic balloon valvuloplasty to show that 10-year survival free from surgical therapy was 59% for group <1 month and 70% for group ≥1 month [41]. Concordant were the results of Pedra *et al*. who followed 87 children >6 months of age at the time of the dilatation (median age 6.9 years) and found that freedom from reintervention was 86%, 67% and 46% after 1, 5 and 12 years respectively, [37] while for neonates, it was 48% at a 5-year period in the study of McCrindle *et al*. [42] and McElhinney *et al.* [43] showing that necessity for reintervention is earlier when balloon dilatation is performed in neonatal age.

A double-balloon percutaneous technique has been used sporadically over the last years. The smaller catheters and balloons, allow for less vascular damage during insertion, manipulation and withdrawal, something particularly useful in cases where the annular diameter is large compared to the femoral vessels [44-47].

In the last years, fetal aortic valvuloplasty has gained popularity. This promising intervention enables avoidance of left ventricular fibrosis, normal left ventricle development and prevention of hypoplastic left heart syndrome [48-51].

PULMONARY VALVE STENOSIS

Pulmonary stenosis is characterized by a dome-shaped pulmonary valve with diffuse leaflet thickening and commissural fusion, blocking the blood flow to the pulmonary artery. Pulmonary valvuloplasty has replaced surgical valvotomy and constitutes the treatment of choice for all ages [52-54]. The major indications are symptomatic pulmonary stenosis and pulmonary stenosis with peak-to-peak valve gradient ≥40mmHg determined by catheterization or echocardiography [30], although Rao suggests ≥50mmHg [55]. Newborns with pulmonary atresia are also candidates, and so are patients with tetralogy of Fallot, mostly for palliative reasons before surgery [56-59]. Dysplastic valves, subvalvular and supravalvular stenosis have lower success rate than typical stenosis [60, 61], though some teams yielded favorable results with dysplastic valves [62, 63]. Widely recommended balloon size has 120-140% the annular diameter [64], although Rao [55] suggests the lowest size range (120-125%), since it ensures lower chances for postoperative pulmonary regurgitation. Balloon inflations are undertaken until a peak-to-peak gradient <30mmHg is achieved. In the end, contrast is injected in the right ventricle, to delineate the leaflets' motion and confirm blood flow across the valve. Postprocedural pulmonary regurgitation and restenosis are the most significant complications. Outcomes of pulmonary balloon dilatation are good as the Valvuloplasty and Angioplasty of Congenital Anomalies Registry pointed out in a study of 533 patients aged between 1 day and 55 years (median 3.7 years). At a median 33-month follow-up freedom from reintervention was 84%, and 23% judged to be suboptimally treated [64]. Rao *et al*. [65] observed 85 patients <20 years (mean 7.0±6.4 years) having undergone pulmonary balloon valvuloplasty to find that 10-year freedom from reintervention was 84%. Transcatheter treatment is superior to surgery, with lower incidence of regurgitation and lower morbidity and mortality rates but relatively higher restenosis rates.

Simultaneous double-balloon dilation has been trialed in several studies with excellent results, yet not superior to the single-balloon technique. Use in older patients with annular diameter >20mm is suggested by most researchers [66-68].

MITRAL STENOSIS

Mitral stenosis (MS) is divided into rheumatic and congenital, with the latter further divided into several subtypes. Percutaneous mitral valvuloplasty has excellent outcome in selected adult patients, while in children it is mostly used for isolated rheumatic MS with excellent results, comparable to surgery [69-73]. A single-balloon (Inoue balloon - Toray Medical Co., Ltd.) and a double-balloon approach have been introduced with the former most commonly implemented [74]. Few trials that compare these techniques have been conducted, showing similar results [75-79]; however, Inoue is considered the gold standard for rheumatic MS, due to ease of use and more established experience [74]. In acquired MS, fusions are easy to tear-off and complications, such as postprocedural regurgitation, are less likely to occur compared to congenital, where valve morphology often makes percutaneous approach tricky. This is why only carefully selected patients with congenital MS and favorable valve morphology (e.g. commissural fusion) are candidates for balloon valvuloplasty, while for other forms surgical intervention is preferable [80, 81]. The most complete series of pediatric patients treated for congenital MS is the McElhinney *et al*. [80] from Boston Children's Hospital, where 108 children (median age 18 months) with severe congenital MS were managed with percutaneous balloon valvuloplasty, surgical valvuloplasty or mitral valve replacement. Percutaneous approach was the most used option and yielded positive results in children with favorable mitral anatomy by improving left ventricular inflow, reducing left atrial pressure and delaying ultimate mitral valve replacement, while surgical treatment was preferable for supramitral ring, concomitant mitral regurgitation and coexistent cardiac anomalies that required cardiotomy. Mitral regurgitation followed 28% of percutaneous valvuloplasties. Freedom from failure of biventricular repair or mitral valve reintervention within 1 year was 55% for mitral balloon dilatation, and 69% for surgical treatment.

TRANSCATHETER PULMONARY VALVE REPLACEMENT

The lifespan of right ventricular outflow tract (RVOT) conduits for the management of complex CHD (most commonly tetralogy of Fallot) is limited as calcification and myocardial remodeling progressively lead to obstruction and/or regurgitation. Endovascular bare stent deployment was used in order to prolong conduit longevity with good results in view of conduit stenosis, but worse in terms of regurgitation. With the study of Bonhoeffer *et al*. [82] on animal models the novel practice of percutaneous pulmonary valve placement was introduced. Melody (Medtronic, Inc.) is the valve currently approved by the FDA, which is a bovine jugular venous valve sutured inside a NuMED Cheatham Platinum stent (NuMed, Inc.) and mounted on a 22-Fr delivering catheter guided with fluoroscopy. A coverage sheath protects the valve during delivery and a balloon-in-balloon system secures exact positioning of the valve. Due to limited available size, RVOT 16-22mm in size is compatible with bioprosthetic valve implantation, although limited new data show potential success beyond this range [83]. Major complications of this practice are stent fracture and endocarditis [84-86]. This novel technique has minimized the need for repeat heart surgery in patients with right ventricle to pulmonary artery conduits and, consequently, improved their quality of life. The US Melody valve trial showed encouraging success rates and uncommon incidence of adverse effects in experienced hands [87, 88]. At the same time, it holds promises for further innovations as it has been used off-label in alternative positions, such as the aortic, mitral, tricuspid valve and the pulmonary artery, with encouraging early results [89-92].

PATENT DUCTUS ARTERIOSUS (PDA)

Ductus arteriosus is of vital significance for the fetus securing blood flow from the pulmonary artery to the aorta

bypassing the lungs. After birth, it normally closes within hours, but it can remain open (patent ductus arteriosus - PDA) with increased risk for pulmonary hypertension, myocardial hypertrophy and heart failure; PDA accounts for 5-10% of all CHD, and its closure can be interventional or surgical. Surgical ligation was the first technique [93] with high success and low complication rates. In 1992, Cambier *et al*. [94] reported successful transcatheter closure of small PDA using Gianturco coils delivered by a small-sized (5 Fr) catheter. Today, coils offer high closure rates and low morbidity in PDAs <4-5mm. Amplatzer Duct Occluder (ADO - St. Jude Medical, Inc.) was introduced and approved by the FDA in the late 1990s. This is a self-expandable, nitinol wire mesh device with a single retention disc and a cylindrical stem, into which polyester fabric is sewn, and which is settled into the PDA. The delivery system involves a delivery cable, a delivery sheath, a loader, a dilator and a pin vise. The device is usually deployed via venous approach. The outcomes in multiple patient series were excellent. In 2004, Pass *et al*. [95] demonstrated the results of a multicenter USA study examining immediate and 1-year results with ADO closure. 439 children (1.8 years median age, 11kg median weight) with moderate-to-large PDAs had an ADO implanted. The 1-year occlusion rate was 99.7% with no deaths and morbidity at 9.4%. Yet, closure is usually seen immediately after device implantation. Today, ADO is used with excellent results and safety in infants and children ≥3kg (manufacturer recommends ≥6kg) and can easily close PDAs up to 16mm. Complications, such as aortic or pulmonary device protrusion with subsequent obstruction (mostly in small infants) and late device embolization, are rare. Although the angled ADO seemed a promising device for the prevention of those complications, it never entered the market [96]. Device embolization risk reduces with correct device size and avoidance of disc intrusion into the PDA. The new Amplatzer Duct Occluder II (ADO II - St. Jude Medical, Inc.) has gained CE mark approval for use in Europe for all PDA types [97]. Its symmetrical double-disc design offers the choice of arterial or venous approach, while the fabric-free technology allows for mounting on a low-profile catheter. Immediate and short-term outcomes have also been examined with the Nit-Occlud PDA-R (pfm medical, Inc.) with favorable results, needing further follow-up [98]. Candidates for percutaneous PDA closure are symptomatic children, asymptomatic children with moderate or large PDA and left-to-right shunt that leads to pulmonary overflow or enlarged left heart chambers and some rare cases of small PDAs. Established pulmonary hypertension with no response to oxygen or nitric oxide and no improvement with temporary balloon occlusion test, as well as fixed right-to-left shunts, are contraindications for PDA closure.

COARCTATION OF THE AORTA (COA)

CoA is a narrowing of the descending aorta right after the origin of the left subclavian artery, that poses an obstruction to the blood flowing to the lower torso and limbs, causing elevated blood pressure in the upper limbs and low blood pressure in the lower limbs, but can also present at a later time, with heart failure. CoA accounts for 5-8% of all CHD. Treatment can be surgical or interventional. Surgical techniques, such as resection of the narrowed segment and end-to-end anastomosis, are preferred in neonates and infants, in which incidence of recoarctation is high with interventional methods [99, 100]. Yet, percutaneous balloon angioplasty can be performed in those patients for palliative reasons and stabilization, bridging them for surgery [101]. Surgical repair is widely used, since symptoms usually present early in life. Existing data also advocate balloon dilatation in neonates and infants with favorable results and some practitioners manage these patients less invasively [102, 103]. Still there is controversy on whether balloon angioplasty should be preferred to surgery for native coarctation. Although short-term outcomes of balloon angioplasty are comparable with those of surgery, in long-term follow-up incidence of restenosis and aneurysm is higher [104], but repeat surgery - usually required after surgical repair - is avoided. The current trend is to perform transcatheter balloon dilatation in children >1 year of age and repeat in restenosis. Discrete coarctation and a resting systolic pressure gradient >20mmHg obtained by catheterization, or less in the presence of collateral vessels or left ventricular dysfunction, are necessary, according to the American Heart Association Indications for Cardiac Catheterization and Intervention in Pediatric Cardiac Disease [30]. Balloon dilatation is also indicated in postsurgical coarctation recurrence [105]. Elongate narrowing or CoA associated with arch hypoplasia may require stent deployment. Stents are mostly implanted in older children and adolescents, who resemble sufficiently to adult corpus, to ensure more durable results, and decrease incidence of aortic aneurysm caused by balloon dilation [106-108] (Fig. **3**). Repeat dilation is necessary with growing, in order the stent to suit perfectly to the aorta. Newer stent technologies, introduced in the last decade, include balloon-expanding and self-expandable stents and covered stents that diminish complications triggered by bare metal

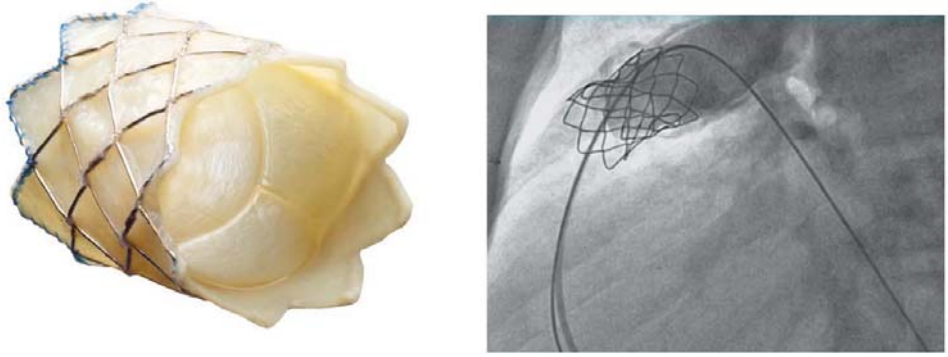

Fig. (3). Stent implantation in a 12-year-old patient with aortic coarctation.

stents, such as aortic wall rupture, aortic dissection and later aneurysm formation [109, 110]. Stent malposition can be seen with any stent type. Although, immediate- and intermediate-term outcomes concerning stent deployment have been observed, long-term outcomes are still unknown.

PULMONARY ARTERY STENOSIS (PAS)

PAS is a narrowing of the pulmonary artery or its peripheral branches and accounts for 2-3% of all CHD. This stenosis hinders the ejection of blood to the pulmonary circulation with only the severe constriction to be associated with clinical manifestations like fatigue, shortness of breath and peripheral edema. The therapeutic modalities implicated in the management of PAS are surgical and percutaneous. Surgery may be chosen in proximal PAS but in most other cases balloon angioplasty is preferred, being the only option for distal PAS. Balloon angioplasty is the treatment of choice for the withdrawal of severe PAS and achieves satisfying immediate relief rates (50-60%). Yet, at follow-up, >15% of patients present with restenosis and require recatheterization [111, 112]. Recurrence is most prevalent in patients <6 years old due to somatic growth. Endovascular stent implantation is used, in order to sustain the newly-opened circulation and achieve long-term results, although redilation may still be needed to overcome restenosis and fit with somatic growth [113, 114]. The most widely used stents are the balloon-expandable Palmaz stents (Cordis, Inc.). Stents are deployed in patients large enough to bear a stent and in selected small-sized patients for transient palliation. The novel technology of cutting balloons has been a notable adjunct for the management of PAS resistant to standard angioplasty and offers better results than high-pressure balloon therapy, yet it is equally safe [115]. They consist of blades or microtomes along the balloon length, which cause micro-incisions to the arterial wall for greater luminal expansion, also maintained at follow-up [116]. Complications of cutting balloon angioplasty are similar to those of the simple balloon angioplasty and include vascular trauma, wall rupture, stent embolization, hemodynamic instability and arrhythmia, among others [117].

PULMONARY VEIN STENOSIS (PVS)

PVS is a rare condition with guarded prognosis characterized by narrowing of the pulmonary veins. It can be acquired (after RF ablation for atrial tachycardia or repair of anomalous pulmonary venous connections) or, most commonly in childhood, congenital. Today, no ideal therapy exists and treatment depends on specialist's experience and center's strategy. The options include balloon angioplasty (simple, high-pressure or cutting), with or without stent, and surgery (sutureless marsupialization). However, none of these achieves sustained results and repeat intervention is frequently required. Surgical treatment may result in satisfying mid-term outcomes, although freedom from reoperation is still low (49% after 5 years) [118, 119]. As for transcatheter techniques, better follow-up results are achieved with stent dilatation. In a study of Prieto *et al*. [120], stent angioplasty was found to be superior to standard balloon angioplasty in adult PVS complicating previous pulmonary vein isolation with immediate success rates 95% and 42% and restenosis rates 33% and 72%, respectively. Restenosis was settled later when a stent had been deployed and was even less frequent if the stent diameter surpassed 10mm. Stents placed in children should have adult-size potential capability for future redilation. Cutting balloons offer immediate relief, but future redilation is usually needed [121]. Some children end up needing lung transplantation [122]; a management considered first-choice only for critically ill patients with poor prognosis [123]. The long-term outcomes of this therapeutic step have not been studied.

AORTOPULMONARY COLLATERALS, CORONARY ARTERY FISTULAS, PULMONARY ARTERIOVENOUS MALFORMATIONS

Aortopulmonary collaterals are blood vessels originated from the aorta and/or the periaortic arteries (e.g. subclavian) and drained to the pulmonary circulation causing a left-to-right shunting. They are mostly found in patients with tetralogy of Fallot, pulmonary atresia and, those with surgically palliated single-ventricle physiology (Fontan, Glenn procedures). Coronary artery fistula constitutes a vascular connection between coronary arteries and a heart chamber or another vessel (e.g. pulmonary artery). Pulmonary arteriovenous malformations are direct arteriovenous connections in the lungs bypassing the capillaries and causing a right-to-left shunting, which can result in hypoxia. The main concept behind these vascular malformations' management is their definitive closure. Today, surgical resection and closure has been limited and transcatheter procedures, i.e. embolization with coils and occlusion via the Amplatzer vascular plugs (AVP - St. Jude Medical, Inc.) are mostly performed. Coils, especially detachable coils, constitute a good choice small to moderate-sized vascular malformations in children, while closure of large vessels is, usually, labored and carries additional risks [124-127]. The Amplatzer vascular plug occluders represent a family of 4 devices (AVP-I, AVP-II, AVP-III, AVP-IV), each with specific indications and advantages [128] (Fig. **4**). AVP-I is the most well-tested and has proved its efficacy in the embolization of vascular

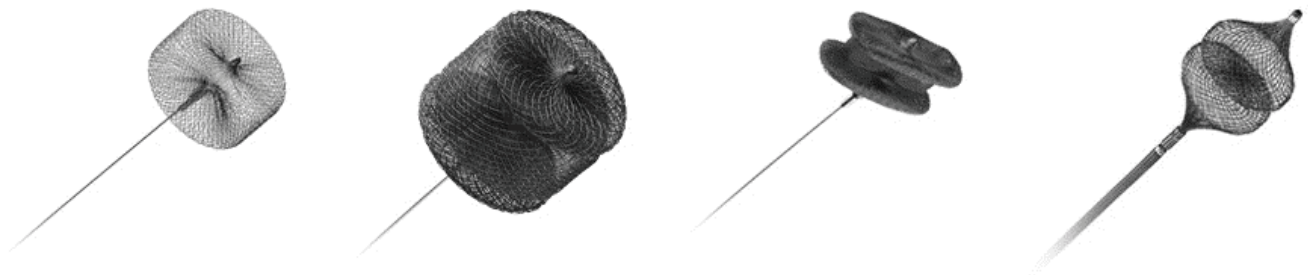

Fig. (4). Amplatzer vascular plug family (I - IV from left to right).

malformations. AVP-II is a 3-segment plug, convenient when rapid occlusion is required, while AVP-III is mostly used in paravalvular leak management. AVP-IV is the latest-generation vascular plug, which, delivered through a 4-Fr catheter, offers the ability for access and device deployment in small and tortuous vascular fields [128, 129]. The AVP devices are considered effective and safe options for closure of moderate-sized to large vascular malformations and continue to unfold further usage capabilities [129-133].

Other devices (e.g. ADO, ASO, CardioSeal) have also been used [134-136], but current literature includes well-documented data only on the use of AVPs. In addition, the long-term efficacy and safety of the AVPs, especially the latest representatives, is not known yet.

ARRHYTHMIAS

Arrhythmias in children can be congenital or acquired, related to a congenital heart defect or not. The majority represents asymptomatic, benign irregularities of the heart rate, which do not require treatment. However, they can sometimes present with constant and worrisome symptoms or pose a life-threatening underlying anomaly, making therapy necessary. During the last two decades, catheter ablation has evolved as a revolutionary therapy in the field of pediatric electrophysiology. Radiofrequency catheter ablation (RFCA), producing low-voltage, high-energy electricity, has been the primordial energy resource used and, soon after, cryoablation (CA), producing excess cold down to -75°C using liquid nitric oxide, emerged. RFCA is a highly effective treatment modality with 95.2% lately reported success rate, according to the Pediatric Radiofrequency Catheter Ablation Registry (90.4% in the initial era of use), with varying complication rate depending on the underlying arrhythmia pathway and age [137]. The corresponding success rate of CA is comparable, but recurrence occurs more frequently [138]. Yet, CA has the advantage of inducing a better-controlled cardiac tissue injury, since with RFCA trauma expands further, even after removal of the catheter tip. Thereby, complications seen with RFCA, like coronary artery occlusion [139] and AV-block [140], become less frequent with CA. Moreover, CA offers the potential of imitation of the post-ablation electric conduction pattern (cryomapping), by chilling cardiac tissue at -30°C to -20°C and causing a temporary electric alteration, before proceeding to definite tissue damage [141-143]. Although CA has been increasingly used during the last decade and has become the treatment of choice for specific arrhythmias [144, 145], a recent retrospective study [146], which included 333 children undergoing RFCA, showed excellent outcomes, with 0.3% major complication rate (one pericardial hemorrhage), no reported AV-block and no deaths, suggesting that proper training and specializing may lead to better outcomes. Further research and RCTs are required, in order to determine credible indications on the use of each technique.

HYBRID PROCEDURES

Hybrid approach is a relatively new innovation, combining surgical and percutaneous techniques. It constitutes a good alternative for children too sick to undergo an open-heart surgery or too small to tolerate typical catheter insertion. These procedures are executed in special operating suites where both surgical and interventional interference is offered [147], alongside with fluoroscopy and transesophageal echocardiography (Fig. **5**).

Hybrid techniques are most commonly performed for hypoplastic left heart syndrome (HLHS) and single-ventricle physiology, perventricular closure of mVSD and perventricular valve implantation.

Untreated HLHS has high mortality in the first month of life. It is characterized by hypoplasia of the left ventricle and the aorta, while systemic oxygenation is achieved through the PDA. Hybrid intervention is indicated either as a stage 1 palliative procedure or as bridge to transplantation [30]. A small sternotomy is undertaken to secure access and shortly after, the right and left pulmonary arteries are banded with PTFE graft segments, in order to enhance blood flow through the PDA to the systemic circulation and reduce pulmonary and right heart overflow. A pursue-string suture is also done on the main pulmonary artery to pass a sheath, through which a catheter will access the PDA and a stent will be implanted to keep PDA open. Eventually, a BAS allows atria blood mixing, offering the left atrium the opportunity to expand. This procedure is performed during the first week of life, being a critical life-saving first step in the management of the newborn. It is a fair alternative of the Norwood palliation, which carries many risks, and it results in a less radical reconstruction, providing a better terrain for im-

Fig. (5). Hybrid operating room in New York-Presbyterian Hospital.

pending bi-directional Glenn shunt, while simultaneously avoids cardiopulmonary bypass.

Hybrid treatment of mVSD is gaining ground in the management of neonates and infants <5kg with hemodynamically significant defect, for which percutaneous intervention alone would bear notable risks. It causes less hemodynamic instability, is safer than transcatheter approach for small patients and less invasive, when compared to surgery, while it eliminates the need for cardiopulmonary bypass [148-151]. First, a purse-string suture is placed on the free right ventricular wall, through which a guidewire is inserted into the right ventricle and, eventually, through the VSD, to the left ventricle. Then, a sheath and dilatator are directed over the guidewire to the left ventricle. An Amplatzer Muscular VSD Occluder can be used to close the defect; first, the left disc is expanded in the left ventricle and then it is gently pushed against the ventricular septal rim, allowing for expansion of the right disc, as well. Deployment is screened with fluoroscopy or echocardiography and the device is released.

Perventricular valve implantation is also an emerging trend, used in access difficulty or increased risk with transcatheter valve implantation or open-heart surgery alone [152-154].

COMPLICATIONS

Complications seem to be relatively rare in pediatric cardiac catheterization, although they cannot be ignored. Older studies showed a complication incidence of 8.8-11.1% in the pediatric age group, either life-threatening or trivial [155, 156], while recent publications displayed higher incidence (>14.7%) in similar age groups and an increase of major adverse events in the sum of adverse events [157-159]. The more complex heart disease encountered nowadays and the higher frequency of neonates and small children catheterization could partly justify these results. Mortality rates do not seem to have changed over the years. In a cohort of 1037 catheterizations [155], Cassidy *et al*. reported 2 deaths directly associated to the catheterization and 2 more (totally 0.39%), in which the procedure contributed to the aggravation of their distress, whereas in the study of Vitiello *et al*. [156], 4952 catheterizations were performed, with 7 deaths associated with the procedure (0.14%), the 5 concerning infants. Recently, similar cohorts reported mortality rates around 0.30%, which ensembles older results [158, 159]. Young age (<6 months and especially neonates), low body weight (<5kg), interventional catheterization, male gender and inpatient status are universally considered independent risk factors for emergence of adverse events [155-164]. Arrhythmias constitute the majority of considerable adverse events, accounting for >20% [155, 156, 158, 159, 164]. Atrial tachycardia and AV-block are the most common usually reverting spontaneously or with minor interference. Vascular complications are very common. The majority concerns arterial thrombosis in the limb (ameliorated with heparin sulfate but rarely needing thrombolytic agents), and topical limb hematoma. Air embolization (usually after repeatedly catheter exchange or large catheter manipulation) and balloon rupture do not usually cause much problem. Device embolization may be prevented with proper heparinization in high-risk cases. Cardiac perforation and cardiac tamponade are severe complications and pericardiocentesis is usually required. Aortic valve dilatation seems to have the highest risk for periprocedural complications [156, 164], while pulmonary atresia, Tetralogy of Fallot RVOT dilatation and aortic coarctation angioplasty, have also considerable complication rates.

SUMMARY

The progress of cardiac catheterization has been swift in the recent years. Catheter-based interventions have become the mainstay of treatment for many cardiac lesions in the pediatric population, due to favorable outcomes, better safety, less need for general anesthesia, and rapid post-interventional recovery. The development of devices for closure of anatomic lesions, the use of stents for maintaining vessel patency, and catheter innovation have expanded the spectrum of heart disease that can be treated this way, while improving therapeutic techniques. Nowadays, surgical management has been limited in many cases or serves as an adjunct to percutaneous treatment in contemporary hybrid procedures. Considering the constantly evolving techniques and technologic development, we believe that cardiac catheterization will continue playing major role in the future management of pediatric heart disease.

CONFLICT OF INTEREST

The authors report no financial relationships or conflicts of interest regarding the content herein.

ACKNOWLEDGEMENTS

The authors would like to thank George D. Chloros, MD for his help in reviewing the manuscript.

REFERENCES

[1] Lechat P, Mas JL, Lascault G, *et al*. Prevalence of patent foramen ovale in patients with stroke. N Engl J Med 1988; 318(18): 1148-52.

[2] Petty GW, Khandheria BK, Chu CP, Sicks JD, Whisnant JP. Patent foramen ovale in patients with cerebral infarction. A transesophageal echocardiographic study. Arch Neurol 1997; 54(7): 819-22.

[3] Overell JR, Bone I, Lees KR. Interatrial septal abnormalities and stroke: a meta-analysis of case-control studies. Neurology 2000; 55(8): 1172-9.

[4] Handke M, Harloff A, Olschewski M, Hetzel A, Geibel A. Patent foramen ovale and cryptogenic stroke in older patients. N Engl J Med 2007; 357(22): 2262-8.

[5] Kutty S, Brown K, Asnes JD, Rhodes JF, Latson LA. Causes of recurrent focal neurologic events after transcatheter closure of patent foramen ovale with the CardioSEAL septal occluder. Am J Cardiol 2008; 101(10): 1487-92.

[6] Wahl A, Meier B, Haxel B, *et al*. Prognosis after percutaneous closure of patent foramen ovale for paradoxical embolism. Neurology 2001; 57(7): 1330-2.

[7] Sievert H, Horvath K, Zadan E, *et al*. Patent foramen ovale closure in patients with transient ischemia attack/stroke. J Interv Cardiol 2001; 14(2): 261-6.

[8] Khairy P, O'Donnell CP, Landzberg MJ. Transcatheter closure versus medical therapy of patent foramen ovale and presumed paradoxical thromboemboli: a systematic review. Ann Intern Med 2003; 139(9): 753-60.

[9] Messe SR, Silverman IE, Kizer JR, *et al*. Practice parameter: recurrent stroke with patent foramen ovale and atrial septal aneurysm: report of the Quality Standards Subcommittee of the American Academy of Neurology. Neurology 2004; 62(7): 1042-50.

[10] Mohr JP, Thompson JL, Lazar RM, *et al*. A comparison of warfarin and aspirin for the prevention of recurrent ischemic stroke. N Engl J Med 2001; 345(20): 1444-51.

[11] Bogousslavsky J, Garazi S, Jeanrenaud X, Aebischer N, Van Melle G. Stroke recurrence in patients with patent foramen ovale: the Lausanne Study. Lausanne Stroke with Paradoxal Embolism Study Group. Neurology 1996; 46(5): 1301-5.

[12] Furlan AJ, Reisman M, Massaro J, *et al*. Closure or medical therapy for cryptogenic stroke with patent foramen ovale. N Engl J Med 2012; 366(11): 991-9.

[13] Schwerzmann M, Windecker S, Wahl A, *et al*. Percutaneous closure of patent foramen ovale: impact of device design on safety and efficacy. Heart (British Cardiac Society) 2004; 90(2): 186-90.

[14] Meier B, Kalesan B, Mattle HP, *et al*. Percutaneous closure of patent foramen ovale in cryptogenic embolism. N Engl J Med 2013; 368(12): 1083-91.

[15] Carroll JD, Saver JL, Thaler DE, *et al*. Closure of patent foramen ovale versus medical therapy after cryptogenic stroke. N Engl J Med 2013; 368(12): 1092-100.

[16] Lip PZ, Lip GY. Patent Foramen Ovale and Migraine Attacks: A Systematic Review. Am J Med 2014; 127(5): 411-20.

[17] Wilmshurst PT, Nightingale S, Walsh KP, Morrison WL. Effect on migraine of closure of cardiac right-to-left shunts to prevent recurrence of decompression illness or stroke or for haemodynamic reasons. Lancet 2000; 356(9242): 1648-51.

[18] Azarbal B, Tobis J, Suh W, Chan V, Dao C, Gaster R. Association of interatrial shunts and migraine headaches: impact of transcatheter closure. J Am Coll Cardiol 2005; 45(4): 489-92.

[19] Wahl A, Praz F, Tai T, *et al*. Improvement of migraine headaches after percutaneous closure of patent foramen ovale for secondary prevention of paradoxical embolism. Heart (British Cardiac Society) 2010; 96(12): 967-73.

[20] Dowson A, Mullen MJ, Peatfield R, *et al*. Migraine Intervention With STARFlex Technology (MIST) trial: a prospective, multicenter, double-blind, sham-controlled trial to evaluate the effectiveness of patent foramen ovale closure with STARFlex septal repair implant to resolve refractory migraine headache. Circulation 2008; 117(11): 1397-404.

[21] Tobis J, Shenoda M. Percutaneous treatment of patent foramen ovale and atrial septal defects. J Am Coll Cardiol 2012; 60(18): 1722-32.

[22] Alaeddini J, Feghali G, Jenkins S, Ramee S, White C, Abi-Samra F. Frequency of atrial tachyarrhythmias following transcatheter closure of patent foramen ovale. J Invasive Cardiol 2006; 18(8): 365-8.

[23] King TD, Thompson SL, Steiner C, Mills NL. Secundum atrial septal defect. Nonoperative closure during cardiac catheterization. JAMA 1976; 235(23): 2506-9.

[24] Du ZD, Hijazi ZM, Kleinman CS, Silverman NH, Larntz K. Comparison between transcatheter and surgical closure of secundum atrial septal defect in children and adults: results of a multicenter nonrandomized trial. J Am Coll Cardiol 2002; 39(11): 1836-44.

[25] Diab KA, Cao QL, Bacha EA, Hijazi ZM. Device closure of atrial septal defects with the Amplatzer septal occluder: safety and outcome in infants. J Thorac Cardiovasc Surg 2007; 134(4): 960-6.

[26] Jones TK, Latson LA, Zahn E, *et al*. Results of the U.S. multicenter pivotal study of the HELEX septal occluder for percutaneous closure of secundum atrial septal defects. J Am Coll Cardiol 2007; 49(22): 2215-21.

[27] Holzer R, de Giovanni J, Walsh KP, *et al*. Transcatheter closure of perimembranous ventricular septal defects using the amplatzer membranous VSD occluder: immediate and midterm results of an international registry. Catheter Cardiovasc Interv 2006; 68(4): 620-8.

[28] Walsh MA, Bialkowski J, Szkutnik M, Pawelec-Wojtalik M, Bobkowski W, Walsh KP. Atrioventricular block after transcatheter closure of perimembranous ventricular septal defects. Heart (British Cardiac Society) 2006; 92(9): 1295-7.

[29] Sullivan ID. Transcatheter closure of perimembranous ventricular septal defect: is the risk of heart block too high a price? Heart (British Cardiac Society) 2007; 93(3): 284-6.

[30] Feltes TF, Bacha E, Beekman RH, 3rd, *et al*. Indications for cardiac catheterization and intervention in pediatric cardiac disease: a scientific statement from the American Heart Association. Circulation 2011; 123(22): 2607-52.

[31] Holzer R, Balzer D, Cao QL, Lock K, Hijazi ZM. Device closure of muscular ventricular septal defects using the Amplatzer muscular ventricular septal defect occluder: immediate and mid-term results of a U.S. registry. J Am Coll Cardiol 2004; 43(7): 1257-63.

[32] Gan C, An Q, Tao K, *et al*. How to choose an occluder for two nearby muscular ventricular septal defects? Ann Thorac Surg 2009; 87(4): 1307-8.

[33] Rashkind WJ, Miller WW. Creation of an atrial septal defect without thoracotomy. A palliative approach to complete transposition of the great arteries. JAMA 1966; 196(11): 991-2.

[34] Hollinger I, Mittnacht A. Cardiac catheterization laboratory: catheterization, interventional cardiology, and ablation techniques for children. Int Anesthesiol Clin 2009; 47(3): 63-99.

[35] Micheletti A, Hislop AA, Lammers A, *et al*. Role of atrial septostomy in the treatment of children with pulmonary arterial hypertension. Heart (British Cardiac Society) 2006; 92(7): 969-72.

[36] Kerstein D, Levy PS, Hsu DT, Hordof AJ, Gersony WM, Barst RJ. Blade balloon atrial septostomy in patients with severe primary pulmonary hypertension. Circulation 1995; 91(7): 2028-35.

[37] Pedra CA, Sidhu R, McCrindle BW, *et al*. Outcomes after balloon dilation of congenital aortic stenosis in children and adolescents. Cardiol Young 2004; 14(3): 315-21.

[38] Ing FF, Boramanand NK, Mathewson J, Maginot K, Perry JC. Transcatheter aortic valvuloplasty assisted by right ventricular pacing. J Am Coll Cardiol 2002; 39(s2): 412-.

[39] McCrindle BW. Independent predictors of immediate results of percutaneous balloon aortic valvotomy in children. Valvuloplasty and Angioplasty of Congenital Anomalies (VACA) Registry Investigators. Am J Cardiol 1996; 77(4): 286-93.

[40] Rocchini AP, Beekman RH, Ben Shachar G, Benson L, Schwartz D, Kan JS. Balloon aortic valvuloplasty: results of the Valvuloplasty and Angioplasty of Congenital Anomalies Registry. Am J Cardiol 1990; 65(11): 784-9.

[41] Fratz S, Gildein HP, Balling G, *et al*. Aortic valvuloplasty in pediatric patients substantially postpones the need for aortic valve surgery: a single-center experience of 188 patients after up to 17.5 years of follow-up. Circulation 2008; 117(9): 1201-6.

[42] McCrindle BW, Blackstone EH, Williams WG, *et al*. Are outcomes of surgical versus transcatheter balloon valvotomy equivalent in neonatal critical aortic stenosis? Circulation 2001; 104(12 Suppl 1): I152-8.

[43] McElhinney DB, Lock JE, Keane JF, Moran AM, Colan SD. Left heart growth, function, and reintervention after balloon aortic valvuloplasty for neonatal aortic stenosis. Circulation 2005; 111(4): 451-8.

[44] Dorros G, Lewin RF, Stertzer SH, *et al*. Percutaneous transluminal aortic valvuloplasty--the acute outcome and follow-up of 149 patients who underwent the double balloon technique. Eur Heart J 1990; 11(5): 429-40.

[45] Beekman RH, Rocchini AP, Crowley DC, *et al*. Comparison of single and double balloon valvuloplasty in children with aortic stenosis. J Am Coll Cardiol 1988; 12(2): 480-5.

[46] Mullins CE, Nihill MR, Vick GW, 3rd, *et al*. Double balloon technique for dilation of valvular or vessel stenosis in congenital and acquired heart disease. J Am Coll Cardiol 1987; 10(1): 107-14.

[47] Dorros G, Lewin RF, King JF, Janke LM. Percutaneous transluminal valvuloplasty in calcific aortic stenosis: the double balloon technique. Cathet Cardiovasc Diagn 1987; 13(3): 151-6.

[48] Allan LD. Rationale for and current status of prenatal cardiac intervention. Early Hum Dev 2012; 88(5): 287-90.

[49] Bacha EA. Impact of fetal cardiac intervention on congenital heart surgery. Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu 2011; 14(1): 35-7.

[50] Matsui H, Gardiner H. Fetal intervention for cardiac disease: the cutting edge of perinatal care. Semin Fetal Neonatal Med 2007; 12(6): 482-9.

[51] Tworetzky W, Marshall AC. Fetal interventions for cardiac defects. Pediatr Clin North Am 2004; 51(6): 1503-13, vii.

[52] Stanger P, Cassidy SC, Girod DA, Kan JS, Lababidi Z, Shapiro SR. Balloon pulmonary valvuloplasty: results of the Valvuloplasty and Angioplasty of Congenital Anomalies Registry. Am J Cardiol 1990; 65(11): 775-83.

[53] Rey C, Marache P, Francart C, Dupuis C. Percutaneous transluminal balloon valvuloplasty of congenital pulmonary valve stenosis, with a special report on infants and neonates. J Am Coll Cardiol 1988; 11(4): 815-20.

[54] Tynan M, Jones O, Joseph MC, Deverall PB, Yates AK. Relief of pulmonary valve stenosis in first week of life by percutaneous baloon valvuloplasty. Lancet 1984; 323(8371): 273.

[55] Rao PS. Percutaneous balloon pulmonary valvuloplasty: state of the art. Catheter Cardiovasc Interv 2007; 69(5): 747-63.

[56] Rao PS, Wilson AD, Thapar MK, Brais M. Balloon pulmonary valvuloplasty in the management of cyanotic congenital heart defects. Cathet Cardiovasc Diagn 1992; 25(1): 16-24.

[57] Godart F, Rey C, Prat A, *et al*. Early and late results and the effects on pulmonary arteries of balloon dilatation of the right ventricular outflow tract in tetralogy of Fallot. Eur Heart J 1998; 19(4): 595-600.

[58] Kreutzer J, Perry SB, Jonas RA, Mayer JE, Castaneda AR, Lock JE. Tetralogy of Fallot with diminutive pulmonary arteries: preoperative pulmonary valve dilation and transcatheter rehabilitation of pulmonary arteries. J Am Coll Cardiol 1996; 27(7): 1741-7.

[59] Sluysmans T, Neven B, Rubay J, *et al*. Early balloon dilatation of the pulmonary valve in infants with tetralogy of Fallot. Risks and benefits. Circulation 1995; 91(5): 1506-11.

[60] Vincent RN, Diehl HJ. Interventions in pediatric cardiac catheterization. Crit Care Nurs Q 2002; 25(3): 37-47.

[61] Ballerini L, Mullins CE, Cifarelli A, *et al*. Percutaneous balloon valvuloplasty of pulmonary valve stenosis, dysplasia, and residual stenosis after surgical valvotomy for pulmonary atresia with intact ventricular septum: long-term results. Cathet Cardiovasc Diagn 1990; 19(3): 165-9.

[62] Rao PS. Balloon dilatation in infants and children with dysplastic pulmonary valves: short-term and intermediate-term results. Am Heart J 1988; 116(5 Pt 1): 1168-73.

[63] Marantz PM, Huhta JC, Mullins CE, *et al*. Results of balloon valvuloplasty in typical and dysplastic pulmonary valve stenosis: Doppler echocardiographic follow-up. J Am Coll Cardiol 1988; 12(2): 476-9.

[64] McCrindle BW. Independent predictors of long-term results after balloon pulmonary valvuloplasty. Valvuloplasty and Angioplasty of Congenital Anomalies (VACA) Registry Investigators. Circulation 1994; 89(4): 1751-9.

[65] Rao PS, Galal O, Patnana M, Buck SH, Wilson AD. Results of three to 10 year follow up of balloon dilatation of the pulmonary valve. Heart (British Cardiac Society) 1998; 80(6): 591-5.

[66] Rao PS. Percutaneous balloon pulmonary valvuloplasty: State of the art. Catheter Cardiovasc Interv 2007; 69(5): 747-63.

[67] al Kasab S, Ribeiro PA, al Zaibag M, Halim M, Habbab MA, Shahid M. Percutaneous double balloon pulmonary valvotomy in adults: one- to two-year follow-up. Am J Cardiol 1988; 62(10 Pt 1): 822-4.

[68] Ali Khan MA, Yousef SA, Mullins CE. Percutaneous transluminal balloon pulmonary valvuloplasty for the relief of pulmonary valve stenosis with special reference to double-balloon technique. Am Heart J 1986; 112(1): 158-66.

[69] Fawzy ME, Stefadouros M, El Amraoui S, *et al*. Long-term (up to 18 years) clinical and echocardiographic results of mitral balloon valvuloplasty in children in comparison with adult population. J Interv Cardiol 2008; 21(3): 252-9.

[70] Lock JE, Khalilullah M, Shrivastava S, Bahl V, Keane JF. Percutaneous catheter commissurotomy in rheumatic mitral stenosis. N Engl J Med 1985; 313(24): 1515-8.

[71] Fawzy ME, Mimish L, Awad M, Galal O, el-Deeb F, Khan B. Mitral balloon valvotomy in children with Inoue balloon technique: immediate and intermediate-term result. Am Heart J 1994; 127(6): 1559-62.

[72] Arora R, Nair M, Rajagopal S, *et al*. Percutaneous balloon mitral valvuloplasty in children and young adults with rheumatic mitral stenosis. Am Heart J 1989; 118(5 Pt 1): 883-7.

[73] Shrivastava S, Dev V, Vasan RS, Das GS, Rajani M. Percutaneous balloon mitral valvuloplasty in juvenile rheumatic mitral stenosis. Am J Cardiol 1991; 67(9): 892-4.

[74] Schievano S, Kunzelman K, Nicosia MA, *et al*. Percutaneous mitral valve dilatation: single balloon versus double balloon. A finite element study. J Heart Valve Dis 2009; 18(1): 28-34.

[75] Kang DH, Park SW, Song JK, *et al*. Long-term clinical and echocardiographic outcome of percutaneous mitral valvuloplasty: randomized comparison of Inoue and double-balloon techniques. J Am Coll Cardiol 2000; 35(1): 169-75.

[76] Leon MN, Harrell LC, Simosa HF, *et al*. Comparison of immediate and long-term results of mitral balloon valvotomy with the double-balloon versus Inoue techniques. Am J Cardiol 1999; 83(9): 1356-63.

[77] Trevino AJ, Ibarra M, Garcia A, *et al*. Immediate and long-term results of balloon mitral commissurotomy for rheumatic mitral stenosis: comparison between Inoue and double-balloon techniques. Am Heart J 1996; 131(3): 530-6.

[78] Sharma S, Loya YS, Desai DM, Pinto RJ. Percutaneous mitral valvotomy using Inoue and double balloon technique: comparison of clinical and hemodynamic short term results in 350 cases. Cathet Cardiovasc Diagn 1993; 29(1): 18-23.

[79] Kasper W, Wollschlager H, Geibel A, Meinertz T, Just H. Percutaneous mitral balloon valvuloplasty--a comparative evaluation of two transatrial techniques. Am Heart J 1992; 124(6): 1562-6.

[80] McElhinney DB, Sherwood MC, Keane JF, del Nido PJ, Almond CS, Lock JE. Current management of severe congenital mitral stenosis: outcomes of transcatheter and surgical therapy in 108 infants and children. Circulation 2005; 112(5): 707-14.

[81] Moore P, Adatia I, Spevak PJ, *et al*. Severe congenital mitral stenosis in infants. Circulation 1994; 89(5): 2099-106.

[82] Bonhoeffer P, Boudjemline Y, Saliba Z, *et al*. Transcatheter implantation of a bovine valve in pulmonary position: a lamb study. Circulation 2000; 102(7): 813-6.

[83] Cheatham SL, Holzer RJ, Chisolm JL, Cheatham JP. The Medtronic Melody(R) transcatheter pulmonary valve implanted at 24-mm diameter--it works. Catheter Cardiovasc Interv 2013; 82(5): 816-23.

[84] Butera G, Milanesi O, Spadoni I, *et al*. Melody transcatheter pulmonary valve implantation. Results from the registry of the Italian society of pediatric cardiology. Catheter Cardiovasc Interv 2013; 81(2): 310-6.

[85] Villafane J, Baker GH, Austin EH, 3rd, Miller S, Peng L, Beekman R, 3rd. Melody pulmonary valve bacterial endocarditis: Experience in four pediatric patients and a review of the literature. Catheter Cardiovasc Interv 2014; 84(2): 212-8.

[86] McElhinney DB, Cheatham JP, Jones TK, *et al*. Stent fracture, valve dysfunction, and right ventricular outflow tract reintervention after transcatheter pulmonary valve implantation: patient-related and procedural risk factors in the US Melody Valve Trial. Circ Cardiovasc Interv 2011; 4(6): 602-14.

[87] Zahn EM, Hellenbrand WE, Lock JE, McElhinney DB. Implantation of the melody transcatheter pulmonary valve in patients with a dysfunctional right ventricular outflow tract conduit early results from the u.s. Clinical trial. J Am Coll Cardiol 2009; 54(18): 1722-9.

[88] McElhinney DB, Hellenbrand WE, Zahn EM, *et al*. Short- and medium-term outcomes after transcatheter pulmonary valve placement in the expanded multicenter US melody valve trial. Circulation 2010; 122(5): 507-16.

[89] Hasan BS, McElhinney DB, Brown DW, *et al*. Short-term performance of the transcatheter Melody valve in high-pressure hemodynamic environments in the pulmonary and systemic circulations. Circ Cardiovasc Interv 2011; 4(6): 615-20.

[90] Michelena HI, Alli O, Cabalka AK, Rihal CS. Successful percutaneous transvenous antegrade mitral valve-in-valve implantation. Catheter Cardiovasc Interv 2013; 81(5): E219-24.

[91] Roberts PA, Boudjemline Y, Cheatham JP, *et al*. Percutaneous Tricuspid Valve Replacement in Congenital and Acquired Heart Disease. J Am Coll Cardiol 2011; 58(2): 117-22.

[92] Gillespie MJ, Dori Y, Harris MA, Sathanandam S, Glatz AC, Rome JJ. Bilateral branch pulmonary artery melody valve implantation for treatment of complex right ventricular outflow tract dysfunction in a high-risk patient. Circ Cardiovasc Interv 2011; 4(4): e21-3.

[93] Gross RE, Hubbard JP. Surgical ligation of a patent ductus arteriosus: report of first successful case. JAMA 1939; 112(8): 729-31.

[94] Cambier PA, Kirby WC, Wortham DC, Moore JW. Percutaneous closure of the small (less than 2.5 mm) patent ductus arteriosus using coil embolization. Am J Cardiol 1992; 69(8): 815-6.

[95] Pass RH, Hijazi Z, Hsu DT, Lewis V, Hellenbrand WE. Multicenter USA Amplatzer patent ductus arteriosus occlusion device trial: initial and one-year results. J Am Coll Cardiol 2004; 44(3): 513-9.

[96] Masura J, Gavora P, Podnar T. Transcatheter occlusion of patent ductus arteriosus using a new angled Amplatzer duct occluder: initial clinical experience. Catheter Cardiovasc Interv 2003; 58(2): 261-7.

[97] Agnetti A, Carano N, Tchana B, *et al*. Transcatheter closure of patent ductus arteriosus: experience with a new device. Clin Cardiol 2009; 32(11): E71-4.

[98] Peirone A, Diaz J, Contreras A, *et al*. Percutaneous closure of the patent ductus arteriosus using the Nit-Occlud PDA-R (reverse) device: initial experience reporting immediate and short-term results. J Invasive Cardiol 2011; 23(12): 513-6.

[99] Rao PS, Galal O, Smith PA, Wilson AD. Five- to nine-year follow-up results of balloon angioplasty of native aortic coarctation in infants and children. J Am Coll Cardiol 1996; 27(2): 462-70.

[100] Rao PS. Long-term follow-up results after balloon dilatation of pulmonic stenosis, aortic stenosis, and coarctation of the aorta: a review. Prog Cardiovasc Dis 1999; 42(1): 59-74.

[101] Bouzguenda I, Marini D, Ou P, Boudjemline Y, Bonnet D, Agnoletti G. Percutaneous treatment of neonatal aortic coarctation presenting with severe left ventricular dysfunction as a bridge to surgery. Cardiol Young 2009; 19(3): 244-51.

[102] Patel HT, Madani A, Paris YM, Warner KG, Hijazi ZM. Balloon angioplasty of native coarctation of the aorta in infants and neonates: is it worth the hassle? Pediatr Cardiol 2001; 22(1): 53-7.

[103] Rao PS, Chopra PS, Koscik R, Smith PA, Wilson AD. Surgical versus balloon therapy for aortic coarctation in infants < or = 3 months old. J Am Coll Cardiol 1994; 23(6): 1479-83.

[104] Hu ZP, Wang ZW, Dai XF, *et al*. Outcomes of Surgical versus Balloon Angioplasty Treatment for Native Coarctation of the Aorta: A Meta-Analysis. Ann Vasc Surg 2014; 28(2): 394-403.

[105] Hellenbrand WE, Allen HD, Golinko RJ, Hagler DJ, Lutin W, Kan J. Balloon angioplasty for aortic recoarctation: results of Valvuloplasty and Angioplasty of Congenital Anomalies Registry. Am J Cardiol 1990; 65(11): 793-7.

[106] Thanopoulos BD, Giannakoulas G, Giannopoulos A, Galdo F, Tsaoussis GS. Initial and six-year results of stent implantation for aortic coarctation in children. Am J Cardiol 2012; 109(10): 1499-503.

[107] Chessa M, Carrozza M, Butera G, *et al*. Results and mid-long-term follow-up of stent implantation for native and recurrent coarctation of the aorta. Eur Heart J 2005; 26(24): 2728-32.

[108] Shah L, Hijazi Z, Sandhu S, Joseph A, Cao QL. Use of endovascular stents for the treatment of coarctation of the aorta in children and adults: immediate and midterm results. J Invasive Cardiol 2005; 17(11): 614-8.

[109] Butera G, Manica JL, Chessa M, *et al*. Covered-stent implantation to treat aortic coarctation. Expert Rev Med Devices 2012; 9(2): 123-30.

[110] Alcibar J, Blanco R, Fernandez L, *et al*. Elective implantation of covered stents for coarctation and recoarctation in adolescents and adults. Rev Esp Cardiol (Engl Ed) 2013; 66(6): 443-9.

[111] Bush DM, Hoffman TM, Del Rosario J, Eiriksson H, Rome JJ. Frequency of restenosis after balloon pulmonary arterioplasty and its causes. The American journal of cardiology. 2000;86(11):1205-9.

[112] Zeevi B, Berant M, Blieden LC. Midterm clinical impact versus procedural success of balloon angioplasty for pulmonary artery stenosis. Pediatr Cardiol 1997; 18(2): 101-6.

[113] Law MA, Shamszad P, Nugent AW, *et al*. Pulmonary artery stents: long-term follow-up. Catheter Cardiovasc Interv 2010; 75(5): 757-64.

[114] Fogelman R, Nykanen D, Smallhorn JF, McCrindle BW, Freedom RM, Benson LN. Endovascular stents in the pulmonary circulation. Clinical impact on management and medium-term follow-up. Circulation 1995; 92(4): 881-5.

[115] Bergersen L, Gauvreau K, Justino H, *et al*. Randomized trial of cutting balloon compared with high-pressure angioplasty for the treatment of resistant pulmonary artery stenosis. Circulation 2011; 124(22): 2388-96.

[116] Bergersen L, Jenkins KJ, Gauvreau K, Lock JE. Follow-up results of Cutting Balloon angioplasty used to relieve stenoses in small pulmonary arteries. Cardiol Young 2005; 15(6): 605-10.

[117] Holzer RJ, Gauvreau K, Kreutzer J, *et al*. Balloon angioplasty and stenting of branch pulmonary arteries: adverse events and procedural characteristics: results of a multi-institutional registry. Circ Cardiovasc Interv 2011; 4(3): 287-96.

[118] Devaney EJ, Chang AC, Ohye RG, Bove EL. Management of congenital and acquired pulmonary vein stenosis. Ann Thorac Surg 2006; 81(3): 992-5; discussion 5-6.

[119] Yun TJ, Coles JG, Konstantinov IE, *et al*. Conventional and sutureless techniques for management of the pulmonary veins: Evolution of indications from postrepair pulmonary vein stenosis to primary pulmonary vein anomalies. J Thorac Cardiovasc Surg 2005; 129(1): 167-74.

[120] Prieto LR, Schoenhagen P, Arruda MJ, Natale A, Worley SE. Comparison of stent versus balloon angioplasty for pulmonary vein stenosis complicating pulmonary vein isolation. J Cardiovasc Electrophysiol. 2008; 19(7): 673-8.

[121] Seale AN, Daubeney PE, Magee AG, Rigby ML. Pulmonary vein stenosis: initial experience with cutting balloon angioplasty. Heart (British Cardiac Society) 2006; 92(6): 815-20.

[122] Bharat A, Epstein DJ, Grady M, *et al*. Lung transplant is a viable treatment option for patients with congenital and acquired pulmonary vein stenosis. J Heart Lung Transplant 2013; 32(6): 621-5.

[123] Holt DB, Moller JH, Larson S, Johnson MC. Primary pulmonary vein stenosis. Am J Cardiol 2007; 99(4): 568-72.

[124] Harikrishnan S, Bimal F, Ajithkumar V, *et al*. Percutaneous treatment of congenital coronary arteriovenous fistulas. J Interv Cardiol 2011; 24(3): 208-15.

[125] Xie CH, Xia CS, Gong FQ, Zhou YB, Zhu WH. Interventional occlusion of congenital vascular malformations. World J Pediatr 2009; 5(4): 296-9.

[126] Goldstein BH, Aiyagari R, Bocks ML, Armstrong AK. Hydrogel expandable coils for vascular occlusion in congenital cardiovascular disease: a single center experience. Congenit Heart Dis 2012; 7(3): 212-8.

[127] Reeves ER, Jahromi BS, Ling FS. Coil embolization of a coronary artery to left ventricular fistula using detachable coils. Catheter Cardiovasc Interv 2013; 82(1): 155-8.

[128] Wang W, Li H, Tam MD, Zhou D, Wang DX, Spain J. The amplatzer vascular plug: a review of the device and its clinical applications. Cardiovasc Intervent Radiol 2012; 35(4): 725-40.

[129] Wiegand G, Sieverding L, Bocksch W, Hofbeck M. Transcatheter closure of abnormal vessels and arteriovenous fistulas with the Amplatzer vascular plug 4 in patients with congenital heart disease. Pediatr Cardiol 2013; 34(7): 1668-73.

[130] Hijazi ZM. New device for percutaneous closure of aortopulmonary collaterals. Catheter Cardiovasc Interv 2004; 63(4): 482-5.

[131] Hill SL, Hijazi ZM, Hellenbrand WE, Cheatham JP. Evaluation of the AMPLATZER vascular plug for embolization of peripheral vascular malformations associated with congenital heart disease. Catheter Cardiovasc Interv 2006; 67(1): 113-9.

[132] Wiegand G, Sieverding L, Kaulitz R, Hofbeck M. Transarterial and transvenous approach for transcatheter closure of a large coronary artery fistula with the Amplatzer vascular plug. Pediatr Cardiol 2009; 30(2): 172-5.

[133] MacDonald ST, Carminati M, Butera G. Initial experience with the Amplatzer Vascular Plug IV in congenital heart disease: coronary artery fistula and aortopulmonary collateral artery embolization. J Invasive Cardiol 2011; 23(3): 120-4.

[134] Behera SK, Danon S, Levi DS, Moore JW. Transcatheter closure of coronary artery fistulae using the Amplatzer Duct Occluder. Catheter Cardiovasc Interv 2006; 68(2): 242-8.

[135] Gamillscheg A, Schuchlenz H, Stein JI, Beitzke A. Interventional occlusion of a large pulmonary arteriovenous malformation with an Amplatzer septal occluder. J Interv Cardiol 2003; 16(4): 335-9.

[136] Apostolopoulou SC, Kelekis NL, Papagiannis J, Hausdorf G, Rammos S. Transcatheter occlusion of a large pulmonary arteriovenous malformation with use of a Cardioseal device. J Vasc Intervent Radiol 2001; 12(6): 767-9.

[137] Kugler JD, Danford DA, Houston KA, Felix G. Pediatric radiofrequency catheter ablation registry success, fluoroscopy time, and complication rate for supraventricular tachycardia: comparison of early and recent eras. J Cardiovasc Electrophysiol 2002; 13(4): 336-41.

[138] Drago F, De Santis A, Grutter G, Silvetti MS. Transvenous cryothermal catheter ablation of re-entry circuit located near the atrioventricular junction in pediatric patients: efficacy, safety, and midterm follow-up. J Am Coll Cardiol 2005; 45(7): 1096-103.

[139] Schneider HE, Kriebel T, Gravenhorst VD, Paul T. Incidence of coronary artery injury immediately after catheter ablation for supraventricular tachycardias in infants and children. Heart Rhythm 2009; 6(4): 461-7.

[140] Van Hare GF, Javitz H, Carmelli D, *et al*. Prospective assessment after pediatric cardiac ablation: demographics, medical profiles,

and initial outcomes. J Cardiovasc Electrophysiol 2004; 15(7): 759-70.

[141] Jensen-Urstad M, Tabrizi F, Kenneback G, Wredlert C, Klang C, Insulander P. High success rate with cryomapping and cryoablation of atrioventricular nodal reentrytachycardia. Pacing Clin Electrophysiol 2006; 29(5): 487-9.

[142] Tuzcu V, Gonzalez YGMB, Schranz D. Diagnosis of tachycardia mechanism with cryomapping in a toddler with complex congenital heart disease. J Interv Card Electrophysiol 2006; 16(1): 59-64.

[143] Wong T, Markides V, Peters NS, Davies DW. Clinical usefulness of cryomapping for ablation of tachycardias involving perinodal tissue. J Interv Card Electrophysiol 2004; 10(2): 153-8.

[144] Drago F, Placidi S, Righi D, *et al*. Cryoablation of AVNRT in Children and Adolescents: Early Intervention Leads to a Better Outcome. J Cardiovasc Electrophysiol; 25(4): 398-403.

[145] Cokkinakis C, Avramidis D, Alexopoulos C, Kirvassilis G, Papagiannis J. Cryoablation of atrioventricular nodal reentrant tachycardia in children and adolescents: improved long-term outcomes with increasing experience. Hellenic J Cardiol 2013; 54(3): 186-91.

[146] Hanslik A, Mujagic A, Mlczoch E, *et al*. Radiofrequency catheter ablation can be performed with high success rates and very low complication rates in children and adolescents. Acta paediatrica (Oslo, Norway : 1992). 2014.

[147] Kpodonu J. Hybrid cardiovascular suite: the operating room of the future. J Card Surg 2010; 25(6): 704-9.

[148] Haponiuk I, Chojnicki M, Jaworski R, *et al*. Hybrid approach for closure of muscular ventricular septal defects. Med Sci Monit 2013; 19: 618-24.

[149] Michel-Behnke I, Ewert P, Koch A, *et al*. Device closure of ventricular septal defects by hybrid procedures: a multicenter retrospective study. Catheter Cardiovasc Interv 2011; 77(2): 242-51.

[150] Diab KA, Cao QL, Hijazi ZM. Perventricular closure of muscular ventricular septal defects: How do I do it? Ann Pediatr Cardiol 2008; 1(1): 27-33.

[151] Crossland DS, Wilkinson JL, Cochrane AD, d'Udekem Y, Brizard CP, Lane GK. Initial results of primary device closure of large muscular ventricular septal defects in early infancy using perventricular access. Catheter Cardiovasc Interv 2008; 72(3): 386-91.

[152] Holoshitz N, Ilbawi MN, Amin Z. Perventricular Melody valve implantation in a 12 kg child. Catheter Cardiovasc Interv 2013; 82(5): 824-7.

[153] Wiegerinck EM, Cocchieri R, Baan J, Jr., de Mol BA. Hybrid coronary artery bypass grafting and transaortic transcatheter aortic valve implantation. J Thorac Cardiovasc Surg 2013; 145(2): 600-2.

[154] Simpson KE, Huddleston CB, Foerster S, Nicholas R, Balzer D. Successful subxyphoid hybrid approach for placement of a Melody percutaneous pulmonary valve. Catheter Cardiovasc Interv 2011; 78(1): 108-11.

[155] Cassidy SC, Schmidt KG, Van Hare GF, Stanger P, Teitel DF. Complications of pediatric cardiac catheterization: a 3-year study. J Am Coll Cardiol 1992; 19(6): 1285-93.

[156] Vitiello R, McCrindle BW, Nykanen D, Freedom RM, Benson LN. Complications associated with pediatric cardiac catheterization. J Am Coll Cardiol 1998; 32(5): 1433-40.

[157] Bergersen L, Gauvreau K, Jenkins KJ, Lock JE. Adverse event rates in congenital cardiac catheterization: a new understanding of risks. Congenital heart disease. 2008;3(2):90-105.

[158] Bergersen L, Marshall A, Gauvreau K, *et al*. Adverse event rates in congenital cardiac catheterization - a multi-center experience. Catheter Cardiovasc Interv 2010; 75(3): 389-400.

[159] Mori Y, Takahashi K, Nakanishi T. Complications of cardiac catheterization in adults and children with congenital heart disease in the current era. Heart Vessels 2013; 28(3): 352-9.

[160] Stanger P, Heymann MA, Tarnoff H, Hoffman JI, Rudolph AM. Complications of cardiac catheterization of neonates, infants, and children. A three-year study. Circulation 1974; 50(3): 595-608.

[161] Cohn HE, Freed MD, Hellenbrand WF, Fyler DC. Complications and mortality associated with cardiac catheterization in infants under one year: a prospective study. Pediatr Cardiol 1985; 6(3): 123-31.

[162] Rhodes JF, Asnes JD, Blaufox AD, Sommer RJ. Impact of low body weight on frequency of pediatric cardiac catheterization complications. Am J Cardiol 2000; 86(11): 1275-8, A9.

[163] Bennett D, Marcus R, Stokes M. Incidents and complications during pediatric cardiac catheterization. Paediatr Anaesth 2005; 15(12): 1083-8.

[164] Mehta R, Lee KJ, Chaturvedi R, Benson L. Complications of pediatric cardiac catheterization: a review in the current era. Catheter Cardiovasc Interv 2008; 72(2): 278-85.