REVIEW

Transcatheter closure of patent ductus arteriosus: Past, present and future

Fermeture percutanée du canal artériel : passé, présent et avenir

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Summary This review aims to describe the past history, present techniques and future directions in transcatheter treatment of patent ductus arteriosus (PDA). Transcatheter PDA closure is the standard of care in most cases and PDA closure is indicated in any patient with signs of left ventricular volume overload due to a ductus. In cases of left-to-right PDA with severe pulmonary arterial hypertension, closure may be performed under specific conditions. The management of clinically silent or very tiny PDAs remains highly controversial. Techniques have evolved and the

Abbreviations: ADO, Amplatzer Duct Occluder; ADO II, second-generation Amplatzer Duct Occluder; ADO II AS, second-generation Amplatzer Duct Occluder with additional sizes; MPA, main pulmonary artery; PAH, pulmonary arterial hypertension; PDA, patent ductus arteriosus.
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Transcatheter PDA closure

Background

Since the first surgical patent ductus arteriosus (PDA) closure by Gross and Hubbard in 1939 and the later transcatheter PDA closure by Portmann et al. in 1967, there have been many significant developments in the devices used to close a PDA [1,2]. In the past 20 years, transcatheter closure has become the leading approach to closure of most PDAs [3]. This review aims to describe past history, present techniques and future directions in transcatheter treatment of PDA.

Patent ductus arteriosus

The ductus arteriosus is a vascular structure that connects the left pulmonary artery near its origin to the descending aorta just after the left subclavian artery; it is an essential foetal structure that closes spontaneously in about 90% of full-term infants during the first 48 hours of life. Persistent patency of the PDA beyond a few weeks is considered abnormal and is mainly encountered in neonates with ventilatory or circulatory abnormalities or in premature infants. Formally speaking, PDA is considered a form of congenital heart disease, defined as a persistent patency beyond the third month of life in term infants [4]; it can be associated with various other congenital heart diseases. In the adult PDA is usually an isolated lesion.

In full-term children, the reported incidence of PDA is approximately 1 per 2000 live births, accounting for 5–10% of all congenital heart diseases [5]. However, addition of the ‘silent’ PDA dramatically increases its incidence to 1 per 500 live births [6]. PDA is a common problem in premature neonates and extremely-low-birthweight infants, being found in 65% of neonates with a birthweight ≤1000 g, and is associated with various neonatal morbidities [7]. The female to male ratio is 2:1 in most reports [4].

Due to several genetic or environmental factors, the ductus may remain patent, causing a left-to-right shunt at the arterial level, pulmonary overcirculation and left heart volume overload. The magnitude of shunting depends on the flow resistance of the ductus and the pressure gradient between aorta and pulmonary arteries. This gradient is dynamic, systolic and diastolic, depending on cardiac output and both systemic and pulmonary vascular resistances [8,9]. PDA has a broad spectrum of clinical manifestations, varying from asymptomatic heart murmur to congestive heart failure or Eisenmenger’s syndrome. The natural history of the PDA largely depends upon its size, the magnitude of the shunt and the pulmonary vascular resistances. Patients with a moderate left-to-right shunt may remain

Transcatheter approach to PDA closure is now feasible and safe with current devices. Coils and the Amplatzer Duct Occluder are used most frequently for PDA closure worldwide, with a high occlusion rate and few complications. Transcatheter PDA closure in preterm or low-bodyweight infants remains a highly challenging procedure and further device and catheter design development is indicated before transcatheter closure is the treatment of choice in this delicate patient population. The evolution of transcatheter PDA closure from just 40 years ago with 18 F sheaths to device delivery via a 3 F sheath is remarkable and it is anticipated that further improvements will result in better safety and efficacy of transcatheter PDA closure techniques.

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asymptomatic for years. However, historical series have shown that chronic volume overload may ultimately lead to severe complications, such as congestive heart failure, atrial arrhythmias, irreversible hypertensive pulmonary vascular disease, endarteritis and, rarely, ductus aneurysm or acute aortic dissection [9–14].

PDA can be managed by medical, surgical or transcatheter treatment. Non-selective cyclo-oxygenase inhibitors have received the US Food and Drug Administration’s approval for the pharmacological treatment of PDA; their use results in successful PDA closure in 75–93% of cases [15]. However, this efficacy has to be balanced with their significant potential adverse effects on other organ perfusion. Moreover, indications for treatment remain a controversial topic, as 40% of PDAs close spontaneously, even in extremely-low-birthweight neonates. Thus, although efficacious for medical closure of the PDA in the premature infant, a careful assessment of risk/benefit is critical when deciding whether cyclo-oxygenase inhibitors should be used and this decision must be individualized to the particular patient. Guidelines for managing PDA in very-low-birthweight infants have been proposed to clarify this issue [16]. Surgical closure is generally indicated in neonates in whom prostaglandin inhibitors have failed to close the PDA or in cases where prostaglandin inhibitors are contraindicated. The surgical approach consists of PDA ligation or division and is performed via left posterior lateral thoracotomy or, in some experienced hands, by a minimally invasive technique via video-assisted thoracoscopic surgery [17]. In older patients, surgical closure remains the treatment of choice in the rare patients with a ductus too large for device closure or with unsuitable anatomy, such as aneurysmal ductus [9]. In most reports, surgical PDA closure allows a complete closure rate of 94–100% with a 0–2% mortality rate [18,19]. The most common complications of surgical ductal intervention include pneumothorax, bleeding and recurrent laryngeal nerve injury. Although extremely efficacious and safe for the closure of PDAs, the surgical approach may be associated with greater morbidity and postoperative pain than transcatheter techniques and these factors have been the most common reasons that percutaneous PDA closure has rapidly become the first choice for PDA closure in the appropriate patient.

The past: proof of the concept

PDA was the first congenital heart disease treated by percutaneous intervention. In 1966, Portsmann et al. performed the first transcatheter closure of a PDA without thoracotomy in a 17-year-old boy [2]. The device used was an Ivalon plug, introduced through an 18 F femoral arterial sheath and travelling on a percutaneously laid transdiscal arteriovenous guide wire. Based on this technique, PDA closure was performed in 197/208 patients (94.7%, age 5–62 years) between 1967 and 1985. The reduced procedural time, lack of need for a thoracotomy and shorter length of hospital stay observed with this approach supported further developments of the procedure [20]. However, the major concern regarding the initial ‘Portsmann plug’ approach was the large size of the arterial delivery sheath, limiting its use in paediatric patients. In 1976, Rashkind et al. developed a transcatheter technique suitable for use in small children, leading to the first successful report 2 years later in an infant weighing 3500 g [21]. The custom-fabricated prototype closure system consisted of a single-foil-disc hooked prosthesis connected to a pin-eye-sleeve attachment-release mechanism. The system was then redesigned and a hookless double-disc system with a pin-eye-sleeve attachment-release mechanism was developed (Rashkind PDA Occluder System). Two polyurethane discs mounted on opposing three- or four-arm spines were assembled, resembling two umbrellas. The first clinical results in 146 patients treated with the Rashkind PDA Occluder System were published in 1987. Successful closure was accomplished in 94 patients (66%), with device embolization in 19 patients (15%) [22]. Although the methods introduced by Portsmann et al. and Rashkind et al. showed advantages over surgical closure, the delivery catheter remained large and bulky, limiting its widespread use. Portsmann’s Ivalon plug required a 13 F to 28 F femoral arterial access and Rashkind’s double-disc device was delivered through an 8 F to 11 F femoral venous access. Additionally and importantly, the success rates for transcatheter PDA closure using these two initial devices were still significantly worse than results reported with the more standard surgical approach.

Sideris et al. developed a self-adjustable PDA device that was modified into a buttoned device that could be delivered through a 7 F sheath. The adjustable length of the loop allowed closure of all types of and large PDAs [23]. Other similar devices, such as the Botallo occluder and the Lock Clamshell device, were developed and transcatheter PDA occlusion became widely available and was used as an alternative to surgery in the early 1990s [24]. These devices were gradually abandoned because of a high incidence of residual leak and subsequent persistent risk of endarteritis, device instability or other major complications [25–27]. Thus, despite initial widespread enthusiasm, reproducible and safe percutaneous PDA closure proved to be more difficult than initially estimated.

Further research was done to develop a device that could address many of the problems of the earlier devices. Some of the important features that were still not achieved were delivery of the device via a small-sized catheter, repositioning of the device multiple times until ultimately released, retrieval of the device easily if necessary, and the ability to allow for complete closure without causing any aortic or pulmonary artery obstruction or damage [28]. The introduction of embolization coils and the Amplatzer Duct Occluder (ADO, Saint Jude Medical, Minnesota) addressed many of these concerns.

Since the initial reports, the success rates of several techniques of duct closure with embolization coils have continued to improve [29,30]. The immediate success rate ranged from 75% to 95% and the rate of closure was inversely related to the size of the ductus and dependent on the experience of the operator. Additionally, the coil technique, although inexpensive and feasible via small catheters, was not suitable for all ducts and was associated with a higher than acceptable rate of coil embolization, particularly in the setting of the large ductus.
The ADO was introduced to address many of the deficiencies of coil embolization techniques. It is a self-expandable repositionable mushroom-shaped device made from a 0.004-inch-thick nitinol wire mesh with Dacron patches within. In 1998, Masura et al. reported the initial successful experience with the ADO in 24 patients using an antegrade approach and a transvenous 6 F delivery sheath [31]. Pass et al. later confirmed these results in a multicentre trial in the USA that confirmed the safety and effectiveness of ADO use for transcatheter PDA closure. ADO and coils are currently the preferred technique for catheter closure of PDA worldwide, with most operators using coils for smaller ducts (in which the likelihood of success is great) and the ADO for larger PDAs.

**The present: daily practice in the catheterization lab**

Transcatheter PDA occlusion has become the treatment of choice for most PDAs in term infants, children and adults [3]. Although age and size are not a consideration when planning surgical closure, transcatheter closure is usually delayed, if feasible, until later in the first year of life, mostly because of the risks of peripheral vascular injury.

**Precatheterization care**

Most of these patients have no associated structural heart disease. The clinical examination demonstrates the PDA continuous murmur in the expected location. The electrocardiogram is often normal. Active infection is ruled out. Transthoracic echocardiography aims to identify any potential associated lesions, to assess left ventricular volume diameters and function, to assess PDA size and, finally, to assess pulmonary arterial pressure. The echocardiogram is very useful in determining if PDA closure is, in fact, indicated. Although it was previously believed that all PDAs identified should be closed, with more relaxed recommendations regarding subacute bacterial endocarditis prophylaxis in the setting of the ductus, small haemodynamically-insignificant PDAs with no evidence for left atrial or left ventricular enlargement are often not closed.

**Angiographical classification**

Following a brief assessment of the haemodynamics, PDA closure always begins with an aorticogram to precisely assess the aortic arch and PDA characteristics, as the ductus arteriosus may persist in a wide variety of sizes and configurations (Fig. 1). Krichenko et al. described a useful angiographical classification for guidance of transcatheter PDA closure [32]. Ductal anatomy in the lateral projection is classified into five categories: type A is a conical ductus, with a well-defined aortic ampulla and constriction at its pulmonary end; type B is a large and very short ductus, mimicking an aortopulmonary window-like structure; type C is a tubular duct, of varying length, without any constriction at its pulmonary end; type D is more complex, with multiple constrictions on the ductus; type E is an elongated ductus, frequently seen in ex-premature babies. This initial angiography is performed with a 4 F or 5 F pigtail catheter positioned in the proximal descending aorta in the straight lateral view. Other projections may be helpful, such as 30° right anterior oblique projections in the left-sided aortic arch, 30° left anterior oblique projections in the right-sided aortic arch and, eventually, a combined left anterior oblique 30°, cranial 30° to open up the pulmonary artery bifurcation and show the proximal left pulmonary artery (for dextrocardia, it is the right anterior oblique equivalent).

**Coil occlusion**

Coil occlusion is a safe and effective procedure for small PDA closure (Fig. 2). According to the 3:1 principle, the coil is the chosen strategy if the total ductal length is more than three times the narrowest diameter of the PDA [33]. Others have simply used minimal ductal diameter < 1.5–2 mm as an indication for coil implantation, as device implantation in such small PDAs can be challenging. Coils are restricted to small Krichenko type A1 or E PDAs, which constitute the vast majority of PDAs. Residual shunting and coil embolization are more likely to occur if used in shorter ducts or in ducts > 3 mm diameter [34].

The most commonly used approach is an arterial retrograde one, but delivery of a coil to the ductus has been described for both the anterograde and retrograde
Figure 2. Coil occlusion of a patent ductus arteriosus (PDA). A. Initial aortography in lateral projection shows a small PDA. B. Selective hand-injected angiography through an end-hole catheter just in front of the aortic ampulla of the ductus. C. The coil is advanced to the main pulmonary artery and carefully deployed in the PDA under fluoroscopic guidance in lateral view. D. After delivery, a small hand injection through the end-hole catheter documents good positioning of the coil and absence of residual leak.

approaches. Femoral access is required in all patients and an appropriately sized sheath is utilized to allow for an adequate angiogram for anatomical definition of the ductus. An initial angiography is performed with a 4F or 5F pig-tail catheter positioned in the proximal descending aorta in lateral and 30° right anterior oblique projections [35]. This injection can be completed by selective hand-injected angiography through an end-hole catheter just in front of the aortic ampulla of the ductus, although a power injection is preferred for more clear anatomical definition. The PDA is crossed by a 0.035 inch wire and a delivery catheter is then advanced over the wire into the main pulmonary artery (MPA). Haemodynamic data are recorded to confirm that the catheter tip is in the MPA. A 0.035 inch or 0.038 inch retrievable or ‘free-hand’ coil is chosen, according to PDA size and length. As a general rule of thumb, a coil is chosen with a loop diameter that is a minimum of two times the diameter of the narrowest segment of the ductus and the length of coil is suitable to allow for four or five coil loops. In the present era, non-ferromagnetic coils (e.g. MREYE) are more commonly used than the prior stainless steel variety. The coil is advanced to the MPA and carefully deployed in the PDA under fluoroscopic guidance in lateral view. Half to one loop is extruded at the end of the catheter. The catheter and the wire are pulled back together until the distal loop is at the desired position, at the MPA side of the ductus. The coil is then delivered with half to one loop at its pulmonary end. After 10 minutes, a small hand injection through the end-hole catheter documents good positioning of the coil and absence of residual leak. In case of residual shunt, the same technique is used to recross the PDA and complete the closure by placing an additional coil.

Device occlusion

Various devices may be used to occlude a PDA according to its morphology (Fig. 3) [36–39]. Only ADO placement is detailed here, as it is the most commonly used device worldwide. The ADO is approved in children aged >6 months and weighing >6 kg; it is placed with an antegrade approach and is usually used for PDAs >2mm with a sufficient aortic ampulla. Both venous and arterial femoral accesses are usually needed, for device progression and simultaneous angiographic controls, respectively. After haemodynamics recording, a 0.035-inch wire is passed anterograde from the MPA, across the ductus to the abdominal aorta. A delivery sheath of appropriate size is then advanced transvenously through the ductus to the descending aorta. The ADO device is positioned through this long 6–8F sheath
under fluoroscopy in the lateral view. The retention skirt is first deployed in the descending aorta and then pulled back into the aortic ampulla. Unsheathing the device under tension leads to ADO placement in the ductus. Device position is confirmed by pigtail aortic angiogram prior to ADO release.

Results and complications

Incomplete closure may occur and has to be treated by repeated procedures, as high-velocity residual shunting may lead to endocarditis or, rarely, haemolysis; these complications are more commonly seen with the use of coils. Embolization is also more common with coils. However the development of controlled-release coils in concert with the development of the ADO for closure of large PDAs has made coil migration a relatively rare event, with a 1% occurrence rate [34]. Embolization may occur to the pulmonary arteries or, rarely, to a systemic artery and requires transcatheter or surgical retrieval [40,41]. Device-induced left pulmonary artery stenosis or coartation of the aorta may occur rarely, particularly in low-bodyweight patients with a large PDA requiring a large device. Careful clinical and echographical follow-up is the rule. In some cases, Doppler flow acceleration may resolve spontaneously with the patient’s growth. In others, obstruction may worsen or become clinically patent, necessitating transcatheter or surgical removal of the device. To avoid this potential complication, aortography is always recommended after device deployment, prior to release and following release of the device. Even after the device has been released, it can be percutaneously retrieved, if necessary, and the duct occluded using a new device. In a multicentre ADO PDA trial in the USA, the ADO was implanted successfully in 99% of patients, with an acute angiographical occlusion in 76% of patients. Complete shunt occlusion was documented in 89% of patients on postcatheterization day 1 and in 99.7% at 1 year [38]. It is important to note that because of the expected delayed closure of the PDA with the ADO device, it is acceptable to leave the catheterization lab with residual shunting, as long as the device is in a good position. However, when using coils for PDA embolization, it is highly recommended that the catheterization is not completed until there is angiographical documentation of complete ductal closure. Peripheral vessels may also be injured by sheaths [42].

Postcatheterization care

Procedures are performed on an outpatient basis or during a short stay in hospital. Clinical attention is given to murmur disappearance and vascular access. Prophylactic antibiotics are routinely administered during the procedure. Postoperative chest X-ray and transthoracic echocardiography are performed to confirm the good position of the device or coil and the lack of residual shunt. These studies also serve as baseline data for future evaluations. Patients with no residual shunt, a normal left ventricle and normal pulmonary artery pressure do not require regular follow-up after 6 months. Patients with left ventricular dysfunction and those with residual pulmonary arterial hypertension (PAH) should be followed at intervals of 1–3 years, depending on severity, including evaluation in specialized centres [3,43].

Closure indications and particular cases

Consensually agreed indications for patent ductus arteriosus closure

Closure of the large haemodynamically-significant PDA is established as the standard of care and can be done safely using transcatheter methods. PDA closure must be performed in all patients with signs of left ventricular volume overload and in those with mild PAH, defined as pulmonary arterial pressures less than two-thirds of systemic pressures or pulmonary vascular resistances less than two-thirds of systemic vascular resistances [3]. Most authorities believe that patients with a continuous murmur and a small PDA, without left ventricular volume overload and normal pulmonary arterial pressures, should also be considered for percutaneous closure to avoid further risks of open PDA-related complications, especially PAH and endocarditis.

Clinically silent patent ductus arteriosus

The appropriate management of the small clinically silent and haemodynamically-insignificant PDA remains controversial [6,44–46]. According to European Society of Cardiology guidelines, PDA closure should currently be avoided in these patients [3]. However, some authors support routine PDA closure, even in a silent ductus, to eliminate the lifelong risk of infective endarteritis [6,44–47]. However, as noted earlier, this risk is so low that antibiotic prophylaxis is no longer recommended [3]. Thus, the low risk of endarteritis must be balanced with the small risks associated with transcatheter PDA closure. The overall prevalence of silent PDA is estimated at 0.5% and, with increasing use of echocardiography, the diagnosis of small and silent PDA is likely to rise [6]. As nobody can truly balance the cumulative risk of PDA closure procedural events and the lifetime risk of silent PDA-related infective endarteritis, to close or not to close a silent PDA currently remains a controversial issue in daily practice.

Loss of continuous murmur when previously heard may lead to diagnostic suspicion of spontaneous ductal spasm. Ductal spasm may also occur during the process of closing a ductus and may result in inaccuracy in ductal measurement. This error may lead to coil occlusion or undersized device occlusion, with subsequent coil/device embolization [48]. Operators must be aware of this issue to avoid underestimating the true ductal size. In fact, it may be a reasonable ‘rule of thumb’ to always assume that the ductus being measured is slightly larger than the angiographical measurement when choosing the appropriate ductal occlusive device and size.

Patent ductus arteriosus in preterm and low-bodyweight infants

The PDA in preterm infants can have significant adverse consequences, increasing pulmonary blood flow, leading to
pulmonary oedema, prolonged ventilation, potential risks of barotrauma, hyperoxygenation, bronchopulmonary dysplasia and chronic lung disease. Significant left-to-right shunting in preterm infants may also be associated with necrotizing enterocolitis, intraventricular haemorrhage and death [8,49,50]. Current therapeutic strategy includes medical treatment with non-steroidal anti-inflammatory agents [50] or, in refractory PDA, surgical ligation by thoracotomy, which can be done in the intensive care unit. Mortality varies according to reports, but, in general, this is a safe surgery that is rarely associated with significant morbidity or mortality in the low-birthweight infant [51]. Recent epidemiological studies have shown a possible association between surgical PDA ligation and impaired neurological development, retinopathy and chronic lung disease [49–56]. However, given the population of patients in which surgical PDA closure is performed, it is difficult to know if this association is causal in nature.

Some authors have reported their initial experience to offer a transcatheter alternative and avoid thoracotomy and its subsequent morbidity [54]. The transcatheter approach is limited in low-bodyweight infants because of sheath size, stiffness of the delivery system, protrusion risk of the device in the left pulmonary artery or aorta and technical difficulties for device retrieval if needed [57]. Despite current manufacturer recommendations, ADO has been evaluated for 'off-label' PDA closure in small infants, to avoid thoracotomy and its subsequent morbidity [54]. In a large French multicentre study, 58 infants weighing < 6 kg underwent attempted PDA closure with the ADO [52], with an 89.7% success rate. Procedure-related mortality and major and minor complications rates were 1.7%, 6.9% and 31.0%, respectively, leading the authors to support surgery as the first-line therapy in low-bodyweight infants. By contrast, Dimas et al. reported a more favourable experience in 62 patients, with a 94% success rate and no deaths [55]. Francis et al. used coil occlusion with a 3F delivery system in eight infants weighing < 2 kg (range 930–1800 g) [58]. Complete PDA occlusion was obtained in all, without major procedure- or access-related complications, leading some to consider coil occlusion as a feasible and safe strategy in selected symptomatic preterm infants and in experienced hands. In another series of infants weighing < 4 kg under positive pressure ventilation, transcatheter PDA closure was compared with surgical PDA ligation in matched infants. Percutaneous closure of PDA in small infants on respiratory support was shown to be equivalent in safety and efficacy and to offer a shorter recovery time than surgical ligation [53]. Low-bodyweight infants with a small and asymptomatic PDA have to be considered for transcatheter closure when they weigh > 6 kg. However, in carefully selected symptomatic infants, especially if the echocardiogram suggests a conical PDA morphology, PDA occlusion with the ADO may be considered in some children weighing > 2.5 kg and in most children weighing > 4 kg [59]. This latter suggestion has to be balanced with experience of the operators, as surgical PDA ligation remains a safe and feasible alternative in small infants. Growing experience, further development of miniaturization materials and newer devices will probably improve the scope of transcatheter PDA closure in symptomatic preterm and/or low-bodyweight infants in the future.

**Patent ductus arteriosus with severe pulmonary arterial hypertension**

In patients presenting with severe PAH, defined as pulmonary arterial pressures more than two-thirds of systemic pressures or pulmonary vascular resistances more than two-thirds of systemic vascular resistances but still net left-to-right shunt (Qp:Qs > 1.5) or when vasoactive testing (preferably with nitric oxide) or specific PAH therapies demonstrate pulmonary vascular reactivity, PDA closure should be considered [3,8,59]. In a large series of 158 selected patients with isolated PDA and systolic pulmonary artery pressure > 50 mmHg, Zabal et al. showed that percutaneous treatment is safe and effective, with immediate decrease of pulmonary artery pressures, which continued to fall further with time [60].

However, long-standing left-to-right shunting in untreated patients may result in progressive increase in pulmonary vascular resistance. When pulmonary vascular resistances exceed systemic vascular resistances, shunting through the PDA reverses and become right-to-left. In the case of PDA-related Eisenmenger’s pathophysiology, PDA closure must be avoided. In these cases, the ductus may also play an important palliative role [3]. Indeed, although reduced compared with the general population, the life expectancy of Eisenmenger’s syndrome patients is significantly longer in comparison with primary pulmonary arterial hypertension. This has been the rationale for creating a surgical or transcatheter Potts’s shunt in children with suprasystemic idiopathic PAH, perhaps as an attempt to mirror the potential benefits of a PDA-like shunt in the setting of pulmonary hypertension, as is seen in Eisenmenger’s syndrome [61,62].

**Patent ductus arteriosus in adults**

Although rare, isolated PDA in adults remains suitable for percutaneous closure. Ductal anatomy may differ from that seen in childhood, making transcatheter closure technically much more difficult than in children [63]. Surgery may be required in some cases, especially if aneurysmal [64]. However, transcatheter closure of the arterial duct in adults is safe and effective [65,66] and the ADO remains the best-used device in this age group [67]. According to ductal anatomy, various other devices, as well as aortic stent grafts or the Amplatzer muscular ventricular septal defect occluder, have also been reported [63,68,69]. In general, for the older adult with a PDA, transcatheter closure is the preferred approach due to the calcification that is routinely seen in the older adult aorta. Because of this, surgical ligation, as is commonly performed in the young, is not feasible. Most such adult PDAs must be closed using cardiopulmonary bypass with patching of the MPA. Thus, any approach to close an adult PDA in the catheterization laboratory is likely to be of lower risk and safer.

**Tubular patent ductus arteriosus**

Transcatheter closure of tubular PDAs with insufficient aortic ampulla, especially in low-bodyweight infants and adult patients, remains a challenging procedure technically (Fig. 4). A proposal to use devices designed for peripheral
vascular embolization has recently emerged and recent reports have evaluated the Amplatzer Vascular Plug (Saint Jude Medical, Minnesota) and the Amplatzer Vascular Plug II in different anatomical variants, with encouraging results [70]. In our experience in 22 patients, the Amplatzer Vascular Plug IV was also safe and efficient for tubular PDA closure [Baruteau et al., in press].

**Patent ductus arteriosus with interrupted inferior vena cava**

Device closure of PDA with interrupted inferior vena cava may be challenging, as putting the delivery sheath across the ductus from the pulmonary artery may be dramatically difficult. However, most of these cases remain suitable for device occlusion. Some authors have reported feasibility of PDA occlusion with either the ADO or a second-generation ADO (ADO II), despite interrupted inferior vena cava with azygous continuation [71—73].

**Postsurgical recanalization of patent ductus arteriosus**

Although underdetected, patency or recanalization of the arterial duct after surgical ligation, detected by colour-flow Doppler mapping, might be as high as 3.1% [74]; these patients remain suitable for a transcatheter intervention. Crossing the PDA with the delivery sheath is the key issue associated with the procedure, as previous surgical ligation can make recrossing of the ductus challenging. Complete occlusion is generally obtained by ADO or coil implantation.

**The future: new devices and perspectives**

**New devices: the Amplatzer Duct Occluder II and II AS**

The ADO II was released in 2007 and obtained European CE mark approval in 2009, with additional sizes (ADO II AS) available in 2011. The first clinical data with the ADO II were provided by Thanopoulos et al. and Bhole et al., showing good safety and a high occlusion rate [75,76]. The ADO II is a self-expanding self-cantering retrievable device. Device sizes correspond to the connecting waist diameter, ranging from 3 to 6 mm, with two available lengths of 4 and 6 mm. The ADO II is more flexible than the ADO and can be delivered through a 4F or 5F sheath or catheter. Preliminary results are encouraging, without protrusion reported [36,70]. The retention discs are laid flat against the walls of the pulmonary artery and aorta. However, device embolization has been reported [70]. The symmetrical design of the ADO II permits its delivery by either a venous or arterial approach. The occlusion rate is high, with <2% residual shunting at postprocedural day 1 [70]. However, the ADO II and ADO II AS devices have not been widely used to date.

**Perspectives**

Percutaneous PDA closure in preterms and low-bodyweight infants remain the main challenge. A new device generation is expected, with shorter devices, a large choice of available diameters and systems suitable for a 3F or 4F sheath. In a series of 55 preterm infants considered for PDA closure reported by Trefz et al., the mean patient weight was 1018 g (560—2400 g) and the mean ductal length was 4.1 mm (2.5—5.3 mm). Mean diameters of the ductus, left pulmonary artery and descending aorta were 2.2 mm (1.5—3.6 mm), 3 mm (1.5—4.5 mm) and 4.3 mm (2.7—7.8 mm), respectively [77]. While low bodyweight is an independent risk factor for adverse events during cardiac catheterization of infants, special attention will be given to the management of these patients in our catheterization laboratories [65].

As can be seen from this review, there have been profound and significant improvements in the transcatheter approach to the PDA. In the present era, virtually any size of patient can have their PDA closed via a transcatheter approach. However, a few important questions remain. First, there is the question of the small ductus with a murmur but no increased volume on echocardiography. Although most agree that the ‘silent’ duct should not be closed, the new ability to quantify the degree of shunt through a
very small ductus using echocardiography and other imaging modalities gives the cardiologist the ability to determine the actual haemodynamic burden of a very small shunt. Are patients with a Qp:Qs of 1.2:1 really at haemodynamic risk and is that risk greater than the small risks associated with transcatheter closure? The answers are still unclear. Second, questions remain regarding which small infants should undergo PDA closure and how this should be achieved. Although some studies have shown that transcatheter closure is feasible and useful in even the smallest of infants, there are certainly many irreparable catheterization-related risks as the patient size gets smaller. As catheters and delivery systems become increasingly miniaturized, the threshold for transcatheter approaches for these small patients will be lowered. Finally, although newer fluoroscopic laboratories use markedly lower radiation dose than in the recent past, it is clear that further attempts at these procedures with either a lower fluoroscopy dosage or perhaps even no fluoroscopy (with guidance via echocardiography or other modalities) will clearly further improve the safety of PDA closure.

Conclusion
Transcatheter PDA closure is the standard of care in most cases and PDA closure is indicated in any patient with signs of left ventricular volume overload due to a ductus. In cases of left-to-right PDA with severe PAH, closure may be performed under specific conditions. Management of clinically silent or very tiny PDAs remains highly controversial. Techniques have evolved and the transcatheter approach to PDA closure is now feasible and safe with current devices. Coils and ADOs are used most frequently for PDA closure worldwide, with a high occlusion rate and few complications. Transcatheter closure of the PDA in preterm or low-bodyweight infants remains a highly challenging procedure and further device and catheter design development is indicated before transcatheter closure is the treatment of choice in this delicate patient population. The evolution of transcatheter PDA closure from just 40 years ago with 18 F sheaths to device delivery via a 3 F sheath is remarkable and it is anticipated that further improvements will improve the safety and efficacy of transcatheter PDA closure techniques.

Disclosure of interest
The authors declare that they have no conflicts of interest concerning this article.

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