REVIEW

Stents in paediatric and adult congenital interventional cardiac catheterization

Apport des stents pour le cathétérisme interventionnel des cardiopathies congénitales de l’enfant et de l’adulte

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Abbreviations: BIB, Balloon-In-Balloon catheter; CHD, congenital heart disease; CP, Cheatham-Platinum; PA, pulmonary artery; RV, right ventricle; RVOT, right ventricular outflow tract.

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Summary  A 'stent' is a tubular meshed endoprosthesis that has contributed to the development of interventional catheterization over the past 30 years. In congenital heart diseases, stents have offered new solutions to the treatment of congenital vessel stenosis or postsurgical lesions, to maintain or close shunt patency, and to allow transcatheter valve replacement. First, stents were made of bare metal. Then, stent frameworks evolved to achieve a better compromise between radial strength and flexibility. However, almost all stents used currently in children have not been approved for vascular lesions in children and are therefore used "off-label". Furthermore, the inability of stents to follow natural vessel growth still limits their use in low-weight children and infants. Recently, biodegradable stents have been manufactured and may overcome this issue; they are made from materials that may dissolve or be absorbed in the body. In this review, we aim to describe the history of stent development, the technical characteristics of stents used currently, the clinical applications and results, and the latest technological developments and perspectives in paediatric and adult congenital cardiac catheterization.

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Background

Since the first report of transcatheter balloon dilation of pulmonary stenosis in 1953 [1], balloon angioplasty has been widely used for many valvular and vascular congenital lesions [2–5]. However, ineffective relief of obstruction and vessel damage have been observed [3–5]. A 'stent' is a tubular meshed endoprosthesis that has contributed to overcoming these issues [4,6–8]. In this general review, we will first describe the pioneering reports of stents development. Next, we will investigate the technical aspects of the available stents. Concepts sustaining the use of stents in congenital heart disease (CHD) catheterization, as well as clinical applications and complications, will be underlined. Finally, future directions will be discussed.

Historical background

The origins of the word 'stent' remain controversial; it may be an old English word derived from the verb 'stenten'. The Latin root is 'extendere', meaning to stretch out. Conversely, the word may have been first used in 1916 by Jan F. Esser, a Dutch plastic surgeon, to describe a medical prosthesis created by an English dentist, Charles Stent (1807–1885) [9]. In 1964, Charles Dotter suggested that an implantable prosthetic device might be used to maintain the luminal integrity of diseased vessels. A precursor stent was successfully positioned in femoral dog arteries, but with secondary dislocations and narrowing [10]. Therefore, it was not until the early 1980s that stents regained interest, with a self-expandable stent with a memory-of-shape property [11]. The first human intracoronary stent (Wallstent®; Boston Scientific, Natick, MA, USA), made of a self-expandable stainless-steel mesh, was successfully deployed in coronary arteries by Jacques Puel in 1986 in CHU Toulouse [12].

Stents rapidly increased interest in the interventional treatment of CHD. In the mid-1980s, Julio C. Palmaz developed a balloon-expandable stent that was successfully implanted in various locations in 1991 [8]. Later, in the early 2000s, Philipp Bonhoeffer and Younes Boudjemline used a stent as a support to anchor a valve in a right
ventricle-to-pulmonary artery (RV-to-PA) prosthetic conduit with valve dysfunction [13].

The first stent available for use in children was the balloon-expandable closed-cell design Palmaz® stent (Johnson & Johnson Interventional Systems, Warren, NJ, USA) [8]. Since then, many others have been developed, including the Genesis™ stent (Johnson & Johnson Interventional Systems, Warren, NJ, USA) [14], the Cheatham-Platinum™ (CP) stent (NuMED, Hopkinton, NY, USA) [15], the IntraStent™ DoubleStrut™ stent (eV3 Inc., Plymouth, MN, USA) [16] and others. Today, the most commonly used stents are the series of eV3 stents (eV3 Inc., Plymouth, MN, USA), the CP stent [17], the Valeo™ stent (Bard Peripheral Vascular, Tempe, AZ, USA) and valved stents (Melody® valve, Medtronic Inc., Minneapolis, MN, USA; Edwards-Sapien™ Valve, Edwards Lifesciences LLC, Irvine, CA, USA) [13,18—21]. New stents have emerged with promising results in CHD catheterization, such as the AndraStent™ stent (Andramed, Reutlingen, Germany) and the Formula™ stent (Cook Europe, Bjaeverskov, Denmark) [22,23]. Almost all stents used currently in children have not been approved for vascular lesions in children and are used 'off-label'.

Stent design

Stents are categorized according to mechanism of delivery, composition, configuration, size and properties. Stent performance depends on material characteristics, form, fabrication mode and geometry. Performances of stents used in CHD are described in eTables 1—3 in the online-only data supplement.

Stent delivery mechanism

Two stent delivery mechanisms are available. Stents are balloon-expandable or self-expandable. In the balloon-expandable system, the stent is crimped manually onto a balloon or premounted by the manufacturer. The balloon catheter stent is moved forward on an intravascular guidewire through a long sheath. The stent is then deployed in the area of interest by inflating the balloon. The stent final diameter is determined by the inflated balloon diameter. The balloon inflation allows a high radial force during stent implantation to relieve vascular obstruction. Postdilation with a larger balloon is possible to further increase stent diameter [24].

Premounted stents, due to superior nesting to the balloon, have a lower profile and do not require long and large sheaths, enhancing their 'trackability' in reaching tortuous destinations and facilitating their use in small children. In PA stenting, the use of premounted stents seems to be associated with fewer complications [25]. The balloon plays a pivotal role in the success of the stent positioning. The Balloon-In-Balloon catheter (BIB®; NuMED, Hopkinton, NY, USA) was specifically developed to facilitate introduction, delivery and deployment of the balloon-expandable Melody valved stent; it incorporates a BIB balloon and a mechanism with a covering sheath to protect the valve as it is advanced through the right ventricular outflow tract (RVOT) (Figs. 3 and 4; Video 2). Balloon-expandable stents have a foreshortening phenomenon during inflation. The degree of foreshortening depends on the stent configuration and is maximal at larger diameters. Stent foreshortening must be anticipated before delivery to be certain that it will completely cover the treated lesion.

Self-expandable stents are constrained by a covering sheath. After positioning in the area of interest, the covering sheath is withdrawn and the stent regains its original shape [26]. Self-expandable stents are made of an alloy of nickel and titanium, with a memory-of-shape property, but with less radial strength than most balloon-expandable stents and therefore a higher risk of vessel recoil. Once in place, further expansion of the self-expandable stent is not possible, unlike balloon-expandable stents, which can be further dilated at a later time [24]. This property is essential in small children with growing vessels. Many interventionists have advised against the use of self-expandable stents in growing children [25].

Composition

Stents are mostly made of metals, allowing high radial strength. Stainless steel is resistant to corrosion and is easily deformable. Cobalt chromium alloys may allow lower crimping profiles with high radial strength. Stents made with metal get incorporated into the vessel wall and do not have the potential to grow or to be degraded by the organism. A variety of degradable materials have been studied for biodegradable stent design, including polyesters, polycarbonates, bacterial-derived polymers and corrodbile metals such as magnesium and iron [27].

Configuration

Two types of stent frameworks have been designed. The 'slotted-tube' design means that the stent is formed from a unique stalk cut by laser from a tube. Premounted stents are cut in the crimped position, allowing a low profile. The other stent framework consists of multiple circular stalks repeatedly curved as a crown and linked by connectors. The stent is manufactured from a wire, which is bent and welded to a cylindrical meshwork; this leads to more adjustable flexibility and wide size and length ranges, but the radial strength is usually less than that for stents with slotted tubes.

In an 'open-cell' design, geometry does not connect consistently throughout the stent, forming incomplete and non-bridged cells. With expansion, the individual cells merge to form larger open areas. This type of stent has less foreshortening, good conformability and fits well in curved vessels. Depending on the curve of the stent, the cell area may vary. In vessel bifurcation stenting (PA bifurcation, aortic arch), the perfusion of a jailed side branch is unlikely...
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Figure 1. A. A 15-year-old girl with a native aortic coarctation. B. CP8Z39 stent manually crimped onto a Balloon-In-Balloon catheter balloon (diameter 14 mm) and positioned through the coarctation. C. and D. Inner balloon inflation and angiographic control. E. Outer balloon inflation. F. Final result. Ao: aorta; LSCA: left subclavian artery.

to be altered with an open-cell stent. If it happens, a balloon reopening of the struts (‘kissing’) will be easier with this type of stent and with the low number of connectors (Figs. 4 and 5; Video 2).

Alternatively, a stent with many connectors, such as the CP stent, is called a ‘closed-cell’ stent. It has a high radial strength and a high vessel scaffolding area, regardless of the degree of bending. A high scaffolding area allows better protection of a vessel with a parietal tear and prevents parietal tissue hernia between the stent struts.

Covered stents

Some stents are covered by a membrane. Covered stents were originally developed to seal perforated and ruptured arteries. The primary use of covered stents in CHD has been advocated in subatretic coarctation [4], native coarctation associated with patent ductus arteriosus and coarctation combined with aneurysm [7]. Covered stents should not jail vessels, leading to anterograde flow obstruction.

Stent properties: characteristics of the ideal stent in congenital heart disease

Fifteen particular stent properties are expected for maximal performance and are summarized in Table 1. Currently available stents do not have all these requirements. As in a rugby team, in which wingers run faster but are weaker than pillars, the choice of stent will be a compromise between priorities and expected properties. The choice integrates the age and size of the patient, the expected adult dimensions of the vascular structure, the morphology of the lesion to treat and expected future surgical procedures.
**Concepts sustaining the use of stents in congenital heart disease**

Stent clinical applications in catheterization of CHD are summarized in Table 2 and follow recommendations [28].

**Stenting to increase the efficiency of balloon angioplasty**

Balloon angioplasty is used to release vascular obstruction, such as PA stenosis. Balloon angioplasty alone is successful in 60–80% of PA branch angioplasty [5]. Ineffective relief of obstruction results from resistant non-compliant lesions [29] or elastic recoil of the vessel wall. Restenosis also occurs as a result of external compression, intimal tears and natural vessel growth out of the angioplasty zone [5]. Stents exert radial forces that prevent elastic recoil (Figs. 2, 4 and 5; Video 2) [8]. Intravascular stenting provides superior gradient relief and angiographic results compared with conventional balloon angioplasty alone in various congenital vascular lesions [4,30]. Success rates in studies using stents and cutting balloons or high-pressure balloons in pulmonary stenosis and RV outflow conduit stenosis rise to > 90% [29,31]. Stents are used in around 40% of cases of PA angioplasty [32] and are sometimes used as first-step intervention without balloon angioplasty. Transcatheter stent implantation can acutely relieve congenital or postoperative pulmonary vein stenosis in children, but reintervention is common. Larger stent lumen size at implantation is associated with longer stent patency and a lower risk of reintervention [33]. Nowadays, with aggressive balloons and stents, successful relief of congenital vascular stenosis is effective in almost all cases.

**Stenting to increase the safety of balloon angioplasty**

Balloon angioplasty can be complicated by intimal tears, vessel dissection and vessel rupture, particularly during native aortic coarctation dilation [3,4,32]. Intravascular stenting enables scaffolding that compresses dissection flaps against the vessel wall and provides a substrate for smooth neointimal growth. In transcatheter treatment of native aortic coarctation (Fig. 1; Video 1) and recoarctation, primary stenting compared with balloon angioplasty prevents long-term adverse effects of vessel remodelling, leading to restenosis and pseudoaneurysm formation [2,4,7]. Rescue stenting is also performed in RVOT and PA branch angioplasty if balloon angioplasty is complicated by tear with flow obstruction or pseudoaneurysm [29,32]. Primary stenting is preferred over balloon angioplasty in early postoperative vascular lesion dilation to prevent fresh suture line disruption [34]. Covered stents are used in emergency situations...
to rescue perforated vessels; the outer membrane provides excellent sealing of the damaged vessels.

**Stenting to occlude shunt**

Covered stents provide a physical barrier between the vessel lumen and the vessel wall, which is useful to occlude shunt patency, such as fenestrated total cavopulmonary connection (Fig. 5) [35], Mustard baffle leaks (Fig. 6) [36], persistent ductus arteriosus associated with aortic coarctation [7] or Potts shunt [37].

**Stenting to maintain shunt patency**

In neonates with a duct-dependent pulmonary circulation, the surgical creation of an aortopulmonary shunt is recommended if early repair is not feasible to palliate duct natural occlusion. Ductus arteriosus stenting was developed as an alternative option to prevent surgery-related morbimortality [38,39] with similar efficacy [40]. Stents are also used to relieve Blalock-Taussig shunt obstruction [41]. Palliative stenting of patent ductus arteriosus may also be performed in older children and in adults with suprasystemic pulmonary arterial hypertension [42]. A hybrid procedure with ductus arteriosus stenting and bending of the PAs is under investigation as an alternative to Norwood surgery perfusion in infants with hypoplastic left heart syndrome (Fig. 7; Video 3) [43]. Stenting of the interatrial septum after atrial septostomy is also performed occasionally in selected neonatal cases, and even in foetal cases, to maintain reliable long-lasting interatrial communication [44].

**Stenting as a support for percutaneous valve replacement**

Transcatheter valve replacement became feasible by inserting a bovine jugular vein into an expandable stent, and was applied primarily to the pulmonary valve [13]. A balloon-expandable stent is used as a support to anchor and deploy the valve in the target position. Bare stenting of the RVOT leads to free pulmonary regurgitation. A valved stent allows treatment of both RVOT obstruction and pulmonary regurgitation [13,18]. Recoil and fracture of the valved stent have been reported [45]. Thus, conventional stents are also used as a ‘prestenting’ procedure in the ‘landing zone’ of the transcatheter pulmonary valve replacement. The prestenting strengthens the landing zone before valve deployment (Figs. 3 and 4; Video 2) [45].

**Hybrid approach**

Stenting has become an alternative to a variety of surgical interventions, such as in aortic coarctation treatment, with less morbidity [4]. In other cases, such as RV-to-PA obstruction, stenting allows postponement of surgery [22,46,47]. Furthermore, a hybrid approach has been developed, combining step-by-step surgery and stenting, as in rehabilitation of PAs in tetralogy of Fallot with pulmonary atresia and major aortopulmonary collaterals (Fig. 8) [48].
A hybrid procedure combining surgery and stenting is also performed concomitantly in the operating room in selected cases [43].

**Stenting complications in congenital heart disease**

Complications occur in 3.5–19% of cases [25,32,49], resulting in a 2.3% overall procedural mortality [25]. Complication rates are highly dependent on the location of stenting [25]. Arterial duct stenting remains a challenging intervention [25]. Many complications during stent implantation are transient and can be solved without ending the procedure; others may be solved by surgery [50]. Thus, catheterization of CHD with stent implantation should be performed in specialized centres with congenital cardiac surgery. Furthermore, the rate of complications is related to the degree of operator experience [51]. Stent implantation should be performed by highly experienced hands.

**Early embolization and migration**

Stent malpositioning, migration and early embolization are dependent on operator experience [32]; they are the most frequent complications, occurring in 7.7% of all implantations [25].

**Neointimal proliferation and restenosis**

Restenosis seems to be rare, occurring in < 2% of cases [24]. Specific risk factors are stent malpositioning, over-dilation and abnormal underlying vascular tissue [24]. Neointimal proliferation is less frequent (around 4%) with a balloon-expandable stent than with a self-expanding stent (around 28%). However, the restenosis rate seems to differ according to stent location. In PA stenting, a recent report identified a restenosis rate as high as 25%, with the highest incidence among patients with tetralogy of Fallot and multiple aortopulmonary collaterals (Fig. 8), Williams syndrome or Alagille syndrome [6,52].
Figure 5. A. A 41-year-old woman with repaired tetralogy of Fallot and pulmonary atresia had stenosis of both pulmonary arteries. B. IntraStent Max LD 36-12 stent positioned on the right pulmonary artery (RPA); CP8Z34 stent and IntraStent Max LD 36-12 stent positioned on the left pulmonary artery (LPA). C. and D. Right superior lobar artery (RSLA) perfusion altered by stent jailing and improved after reopening of the stent stitches by a kissing balloon.

Table 1  Stent properties: characteristics of the ideal stent in congenital heart disease interventional catheterization.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Radiopacity High radio-opacity facilitates stent positioning before implantation</td>
</tr>
<tr>
<td>2</td>
<td>Low profile A stent with a low profile decreases the delivery sheath size</td>
</tr>
<tr>
<td>3</td>
<td>Good crimpability Premounted stents or easy hand crimping with stability of the stent onto the delivery balloon are expected</td>
</tr>
<tr>
<td>4</td>
<td>High flexibility High flexibility allows delivery in tortuous vessels like pulmonary arteries, gives compliance to the target area and ease of manoeuvrability during deployment</td>
</tr>
<tr>
<td>5</td>
<td>Good conformability A stent with good conformability will fit well with the vessel geometry and curves, and will protect from vessel distortion</td>
</tr>
<tr>
<td>6</td>
<td>No foreshorting A predictable expansion diameter with a low degree of stent foreshortening is expected during stent expansion for precision of positioning and to better match the length of lesion to be treated</td>
</tr>
<tr>
<td>7</td>
<td>High radial strength Stents must have a high radial strength to resist external radial forces of the vessel wall, prevent vessel recoil and keep tight and scarred lesions open</td>
</tr>
<tr>
<td>8</td>
<td>High scaffolding High scaffolding of the vessel is necessary to prevent parietal tissue protrusion and risk of restenosis</td>
</tr>
<tr>
<td>9</td>
<td>Retrievability Stent retrievability and repositioning decrease the risk of malpositioning and embolization</td>
</tr>
<tr>
<td>10</td>
<td>Wide struts Wide struts are expected to maintain blood flow to jailed vessel branches</td>
</tr>
<tr>
<td>11</td>
<td>Soft edges Rounded and soft edges will prevent vascular tears and balloon rupture during delivery</td>
</tr>
<tr>
<td>12</td>
<td>Potential to grow An ideal stent implanted in small children would follow the natural growth of the vessel; on the other hand, a stent must be redilatable until the expected adult diameter is reached</td>
</tr>
<tr>
<td>13</td>
<td>Solidity The framework must be solid enough to resist fracture; loss of integrity decreases the radial strength and increases the risk of restenosis</td>
</tr>
<tr>
<td>14</td>
<td>Imaging compatibility The stent should be compatible with all imaging modalities without artefacts</td>
</tr>
<tr>
<td>15</td>
<td>Biocompatibility Biocompatibility must be high, with resistance to thrombus formation, corrosion and unwanted inflammatory or allergic reactions, and avoidance of neointimal proliferation</td>
</tr>
</tbody>
</table>
Table 2 Stenting applications in congenital heart disease.

<table>
<thead>
<tr>
<th>Stenting localization</th>
<th>Type of stents used most frequently</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stenting to improve efficiency of balloon angioplasty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lobar PA stenosis</td>
<td>Formula(^a), Valeo(^b), Genesis(^c), Express Vascular(^d), coronary stents, IntraStent Max LD</td>
<td>[20,22]</td>
</tr>
<tr>
<td>Main branch PA stenosis</td>
<td>eV3 series(^e), CP8-Zig(^f), Palmaz(^g), Genesis, Andrastent XL(^h)</td>
<td>[17,23,30]</td>
</tr>
<tr>
<td>RVOT obstruction in neonates &amp; infants (palliative procedure)</td>
<td>Coronary &amp; small peripheral bare-metal stents, Formula (^i)</td>
<td>[22,46]</td>
</tr>
<tr>
<td>RVOT obstruction in children &amp; adults</td>
<td>Covered CP8-Zig, CP8-Zig, IntraStent Max LD, Palmaz, Genesis</td>
<td>[17]</td>
</tr>
<tr>
<td>RV-to-PA conduit obstruction</td>
<td>IntraStent Max LD, CP8-Zig, Palmaz, Genesis, Andrastent XL</td>
<td>[17,56]</td>
</tr>
<tr>
<td>Fontan Tunnel obstruction</td>
<td>IntraStent Max LD, CP8-Zig, Palmaz, Genesis, Andrastent XL</td>
<td></td>
</tr>
<tr>
<td>PA rehabilitation in infants</td>
<td>Formula, Valeo, Genesis</td>
<td>[20,22,48]</td>
</tr>
<tr>
<td>Vena cava obstruction</td>
<td>IntraStent Max LD, CP8-Zig, Palmaz, Genesis, Advanta V12(^i)</td>
<td>[17,63]</td>
</tr>
<tr>
<td>Postoperative or congenital PV stenosis</td>
<td>Palmaz, Genesis, covered iCAST(^j), Valeo, coronary stents</td>
<td>[33,63]</td>
</tr>
<tr>
<td><strong>Stenting to improve safety of balloon angioplasty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aortic coarctation or Aortic recoarctation</td>
<td>Covered CP8-Zig, CP8-Zig, IntraStent Max LD, Palmaz, Genesis, covered Advanta V12</td>
<td>[7,15,17,63]</td>
</tr>
<tr>
<td>RVOT</td>
<td>Covered CP8-Zig, CP8-Zig, IntraStent Max LD, Palmaz, Genesis, Advanta V12</td>
<td>[17,63]</td>
</tr>
<tr>
<td>PA dissection or rupture</td>
<td>Covered CP8-Zig, CP8-Zig, IntraStent Max LD, Palmaz, Genesis</td>
<td></td>
</tr>
<tr>
<td>Mustard/Senning baffle stenosis</td>
<td>CP8-Zig, IntraStent Max LD, Andrastent XL, Palmaz, Genesis</td>
<td>[23]</td>
</tr>
<tr>
<td><strong>Stenting to close shunt</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fontan fenestration</td>
<td>Covered CP8-Zig, Advanta V12</td>
<td>[35,63]</td>
</tr>
<tr>
<td>Potts shunt</td>
<td>Covered CP8-Zig</td>
<td>[37]</td>
</tr>
<tr>
<td>Mustard/Senning baffle leaks</td>
<td>Covered CP8-Zig</td>
<td>[36]</td>
</tr>
<tr>
<td><strong>Stenting to maintain shunt</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ductus Arteriosus</td>
<td>Valeo, coronary &amp; peripheral balloon-expandable bare-metal stents, coronary &amp; peripheral self-expandable stents, Palmaz</td>
<td>[38–40,42]</td>
</tr>
<tr>
<td>Atrial septectomy</td>
<td>Coronary balloon-expandable bare-metal stents</td>
<td>[44]</td>
</tr>
<tr>
<td>Blalock-Taussig shunt</td>
<td>Coronary balloon-expandable bare-metal stents, drug-eluting coronary stents</td>
<td>[47]</td>
</tr>
<tr>
<td><strong>Valved stent</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulmonary regurgitation with RV dilation</td>
<td>Melody valve(^k), Edwards-Sapien valve(^l)</td>
<td>[13,18,45]</td>
</tr>
<tr>
<td>RVOT obstruction</td>
<td>Melody valve, Edwards-Sapien valve</td>
<td></td>
</tr>
<tr>
<td>RV-to-PA conduit</td>
<td>Melody valve, Edwards-Sapien valve</td>
<td></td>
</tr>
<tr>
<td>‘Prestenting’ of the landing zone</td>
<td>CP8-Zig, IntraStent Max LD, Palmaz</td>
<td>[45]</td>
</tr>
</tbody>
</table>

AC: aortic coarctation; AR: aortic recoarctation; DA: ductus arteriosus; FT: Fontan tunnel; PA: pulmonary artery; PV: pulmonary vein; RV: right ventricle; RVOT: right ventricular outflow tract.

\(^a\) Cook Europe, Bjaeverskov, Denmark.
\(^b\) Bard Peripheral Vascular, Tempe, AZ, USA.
\(^c\) Johnson & Johnson Interventional Systems, Warren, NJ, USA.
\(^d\) Boston Scientific, Natick, MA, USA.
\(^e\) eV3 Inc., Plymouth, MN, USA.
\(^f\) Cheatham-Platinum™ 8-Zig; NuMED Inc., Hopkinton, NY, USA.
\(^g\) Andramed GmbH, Reutlingen, Germany.
\(^h\) Atrium Medical Corporation, Hudson, NH, USA.
\(^i\) Medtronic Inc., Minneapolis, MN, USA.
\(^j\) Edwards Lifesciences LLC, Irvine, CA, USA.
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Figure 6. A. and B. A covered CP8245 stent implanted through a postsurgical superior vena cava (SVC) occlusion. C. A covered Cheatham-Platinum (CP) stent closes a total cavopulmonary derivation (TCPD) fenestration. D. A CP stent positioned on a Mustard superior baffle stenosis; note the atrial septal defect occluder device closing a residual interatrial shunt. RA: right artery; RPA: right pulmonary artery; SSVB: superior systemic venous baffle.

Stent mismatch

The stented vessel is unable to grow with the child, leading to a relative restenosis of the vessel. Serial dilations of the stents or surgical removal may be required, thus limiting their use in this fast-growing population. Redilation with a larger balloon is efficient for increasing the diameter of previously implanted balloon-expandable stents to accommodate somatic growth (Fig. 8) even with a covered CP stent [24,53]. Fracturing a non-dilatable stent with a high-pressure balloon is another solution for further expanding a stent with vessel mismatch.

Vessel trauma

In native aortic coarctation stenting, aortic wall injury occurs in < 1% of cases, particularly in Turner syndrome [4,54], and occurs even less frequently after PA branch stenting [6]. Such trauma may result in dissection, aneurysm or even vessel rupture. Various interventional therapies address these complications (coil or device occlusion of a PA branch, implantation of a covered stent). Emergency surgery is sometimes required [50].

Compression of adjacent structures

Stent implantation in vascular structures within the chest in patients with CHD may induce mechanical compression of surrounding structures. Coronary artery compression has been described following transcatheter pulmonary valve replacement and angioplasty of the right PA (Video 4) [19,25]. Bronchial compression may also have disastrous consequences [55].

Endocarditis

Endocarditis following stent implantation has been reported rarely [56]. However, since the introduction of valved stents and transcatheter pulmonary valve replacement, great concerns have been raised by reports suggesting endocarditis in 0.88–2.4% of cases per year [57]. Risk factors and pathological mechanisms remain to be elucidated.

Stent fractures

Stent fractures are rare overall, observed in < 3% of cases in patients with CHD [58]. Stent fractures mainly occur in RV-to-PA conduits, with an incidence ranging from 25 to 40% [47,56,58], and in both proximal PAs. In aortic coarctation stenting, fractures have been observed in 8% of cases [59]. In a single-centre report of 764 procedures, no stent fracture was observed in any other location [58]. Incidence also varies widely according to the type of stent [47]. Stent fractures may lead to distal fragment embolization, but they are always asymptomatic. Stent fractures in RV-PA conduits are often associated with restenosis, which may lead to further transcatheter or surgical intervention. Therefore, this issue was an important concern when transcatheter pulmonary valve replacement was initiated, but was resolved by pre-stenting the landing zone to increase its radial strength before valve deployment (Figs. 3 and 4) [45].

Perspectives

Bioresorbable stents

Bioresorbable stents have been developed, with the aim of dissolving after vessel healing, allowing the potential for
late vessel remodelling and growth. Once the stent has disappeared, the vessel can grow with the child, eliminating the need for future surgery or dilation. Bioresorbable stents may also facilitate future intervention in lesions with complex anatomy, such as PA bifurcation lesions leading to jailed vessels. Bioresorbable stents would be of great value in extending interventional treatment of aortic coarctation or recoarctation in neonates and small children [27]. Precur sor work involved a hybrid stent consisting of two metallic halves connected by resorbable sutures implanted in small child’s recoarctation. This stent failed to follow the natural growth of the vessel, but was successfully redilated [60]. Bioresorbable stents may also be valuable for the treatment of PA stenosis in small children [61] and for the rehabilitation of PA in tetralogy of Fallot with pulmonary atresia [48].

The manufacture of bioresorbable stents is challenging. Degradation time is a compromise between radial force and scaffolding that allows vessel healing while degrading over a reasonable time for late vessel remodelling. Most available bioresorbable stents have been developed for coronary artery treatment. Larger diameters are needed for use in CHD [62].

**Covered stents**

The covered CP stent is used most frequently [35,36,53]. However, the polytetrafluoroethylene membrane is fragile and can easily be damaged during stent crimping or stent insertion into the delivery sheath. Thus, the profile is higher and larger sheaths are needed. The polytetrafluoroethylene membrane is poorly compliant, with low flexibility. The covered CP stent can be dilated to a larger diameter [53,63]. The alternative Advanta™ V12 stent (Atrium Medical Corporation, Hudson, NH, USA) has a better profile
Stents in paediatric and adult congenital interventional cardiac catheterization

Figure 8. A 4-year-old girl with type 3 tetralogy of Fallot with pulmonary atresia underwent sequential pulmonary artery rehabilitation and complete surgical repair. Two Valeo stents (8 mm diameter) were positioned on the left pulmonary artery (LPA) and on the main pulmonary artery to the right pulmonary artery (RPA), jailing the LPA. After 4 years, right ventricular pressure was elevated due to bilateral pulmonary artery restenosis. A.–C. Note the scaffolding defect that has favoured intrastent stenosis. B. and D. Postdilation with an Atlas Gold balloon (12 mm) successfully released the restenosis and further expanded the stents (D). RVOT: right ventricular outflow tract.

because the membrane is completely incorporated into the inner and outer parts of a balloon-expandable stent. The stent is premounted on a balloon until it reaches 16 mm and can be gently dilated up to 22 mm, but with less radial strength and more recoil. Thus, the ideal covered stent for use in CHD remains to be developed. Associated with the evolution of stent frameworks and materials, new synthetic and biological membrane components, such as nanoparticles and fibrin, may help to overcome these issues [64].

**Drug-eluting stents**

Drug-eluting stents are coated with an antiproliferative drug that decreases the risk of restenosis in coronary artery disease stenting. Drug-eluting stents are not currently useful in CHD. However, the concept of using a stent as a platform for substance delivery may be interesting. One may wonder if stents coated with vessel growth factors would be useful in the rehabilitation of PAs or in aortic arch hypoplasia, to promote the growth of small vessels. Moreover, in pulmonary arterial hypertension, a drug-eluting stent coated with an antihypertensive substance with progressive release of the drug may be useful in increasing the in situ concentration. This is not just a dream — illustrating this concept, Cabanelas et al. used a drug-eluting stent coated on its endoluminal surface by antihuman CD34 antibodies in children with obstructed Blalock-Taussig shunt. This stent has endothelial progenitor cell-capturing properties, promoting rapid coverage by endothelium, thus decreasing the risk of thrombosis and restenosis [41].

**Stent implantation imaging**

The success of a stent procedure depends on the precision of the positioning. Deployment is a complex procedure performed under fluoroscopic guidance with repeated angiograms. Modern fluoroscopic angiography systems permit rendering of three-dimensional volumetric data sets using rotational angiography; along with magnetic resonance imaging or multidetector-row computed tomography datasets, they can be fused with live fluoroscopy images for road-mapping during therapeutic procedures. Glöckler et al. recently observed that three-dimensional guidance facilitates catheter-based interventions in CHD. Three-dimensional guidance simplifies catheter manipulations and interventions, allows preselection of ideal projection angles and reduces fluoroscopic time and the number of control angiograms [65].

**Conclusion**

Stents have contributed greatly to the development of interventional catheterization for CHD. From the old rigid Palmaz stent to covered and valved stents, technological evolution has further extended their clinical applications. The interventionists have to deal with the number and different properties of available endoprostheses to choose the appropriate stent for each case. Results are good and stenting has become a validated alternative to surgery in many lesions. Procedures can still be lengthy and complex but may be facilitated in many cases by fusion imaging and perprocedural three-dimensional guidance. Large sheaths
required for stent deployment limit use and increase the risk of vessel access complications. Miniaturization of delivery systems would facilitate implantation in tortuous and small vessels. The inability of stents to follow natural vessel growth remains an important limitation to their use in growing children. Biodegradable stents with sufficient radial strength but respecting natural vessel growth may further extend the use in infants and neonates.

Disclosure of interest

Sebastien Hascoët reports none.
Alain Fraisse is a consultant for Numed.
Younes Boudjemline is a proctor for Medtronic.

Appendix A. Supplementary data

Supplementary data (Videos 1–4; eTables 1–3) associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.acvd.2014.06.005.

References


