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Review

Technical Modifications for Ductal Stenting in Neonates with Duct-Dependent Pulmonary Circulation

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Abstract: The ductal stenting (DS) is currently an acceptable palliative treatment in newborns suffering with duct-dependent pulmonary circulation. However, this procedure remains technically a challenge in complex ductal morphology, which may eventually lead to detrimental outcomes. This review is mainly focused on pre-procedural planning, essential instruments and practical approaches for DS, and post-procedural care.

Keywords: ductal stenting; duct dependent pulmonary circulation; technique

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Since the first report of ductal stenting (DS) in 1995 [1], this procedure is currently an acceptable alternative palliative option for cyanotic newborns with duct-dependent pulmonary circulation with comparable early mortality, lower medium-term mortality, and lower risk of procedural complications compared with the modified Blalock–Taussig shunt [2,3]. Nevertheless, the procedure can be technically challenging with a failure rate of 16–20% [4,5] and may lead to detrimental complications, such as dissection/rupture of the duct, stent thrombosis, stent embolization, or interruption of the main pulmonary artery branch. Therefore, the operator must pay attention to all the details before, during, and after the procedure. This review provides practical techniques and tips on dealing with common complex ductal morphology: vertical take-off, elongated-tortuous course, and pulmonary coarctation.

1. Problems of Duct Stenting

Even though DS is nowadays an acceptable alternative palliative treatment to surgical systemic to pulmonary artery shunt [3–7], overall, the early stent-related complication rate is 13.2% to 23.1%, including stent migration, stent thrombosis, in-stent restenosis, jailing of the pulmonary artery branches, and pulmonary overcirculation [5–9]. These complications can be reduced by technical modifications, although a few are unavoidable. Therefore, it is compulsory to understand how to deal with each ductus arteriosus (DA) in order to reduce the risks of complications.

The morphology of the DA in duct-dependent pulmonary blood flow can be classified in different ways, which is generally determined by the ductal origin, tortuosity, and supply to the lungs [9,10]. However, not only should the operators consider ductal morphology, but also the ultimate goal of the definitive treatments (whether it is univentricular or biventricular repair) should be taken into account for decision making.

2. Aims of Duct Stenting

The aims of DS are to provide adequate blood flow with equal distribution through the pulmonary circulation in an acceptable time-frame for a particular surgical definitive treatment of each patient. The diameter, the length, and the type of the stent are major factors to be considered for this aim. In general, post-procedural oxygen saturation of 85–90% provides appropriate palliative pulmonary blood flow in patients either univentricular or biventricular heart physiology with duct-dependent pulmonary circulation. In comparison to the patient's size, the larger the implanted stent diameter, the higher the pulmonary blood supplied by the stent. Therefore, proper selection of the stent diameter is a fundamental rule to optimize the pulmonary blood flow. Stent diameter should be selected on the basis of the patient size, ductal morphology, expected duration of palliation, and the type of the next surgical treatment. As recommended by Alwi et al. [11], the stent diameter of 3.5 mm is reasonable to implant in patients weighing 3 kg, 4 mm in those weighing 3–5 kg, and 4.5 mm in those weighing 5 kg and above. In order to avoid post-procedural ductal constriction, the length of the stent should be chosen to cover the entire length of the duct from the proximal aortic end to the distal pulmonary artery end. Overall, the selected stent diameter and length should provide symmetrical and sufficient supply to both the pulmonary arteries.

In early experience of DS, bare metal coronary stents (BMS) have been mostly used. However, the reintervention rate due to in-stent restenosis of BMS is 17% to 25% at 6 months [11–13]. Therefore nowadays, drug-eluting coronary stents (DES) are more commonly used with less luminal loss and less unplanned reintervention [14]. The immunosuppressive drug levels after stent implantation in infants are acceptable [15] and there have been no observed clinically significant adverse outcomes [15,16]. In addition, with the latest generation of the DES, these can be over-expanded from 4 mm up to 5.5 mm. This characteristic provides a room for further dilation in growing infants before they reach ultimate surgical repair. Nonetheless, incorporation of the stent within the vascular wall and acquired rigidity of the pulmonary artery wall after DS may complicate future surgical treatment. The new generation bioabsorbable stent is currently being developed to overcome these drawbacks.

3. Pre-Procedural Assessments and Preparation

3.1. Transthoracic Echocardiogram (TTE)

TTE is the most useful tool for pre-procedural assessment. Nonetheless, TTE is an operator-dependent tool, which may not provide complete information prior to the procedure. As a practical guide, the following details should be obtained from TTE: (1) Overall cardiac morphology, (2) Origin, shape, and length of the DA, and (3) Pulmonary artery connection and presence of associated pulmonary coarctation.

3.2. Cardiac Computed Tomography (CCT) and 3-Dimensional (3D) Planning

CCT and 3D evaluation are not essential in all the cases for pre-procedural planning. However, the DA with multiple turns or obscure anatomy visualized inadequately by conventional TTE are eligible indications for further CCT assessment. This modality provides precise shape, length, constriction of the DA as well as information about the pulmonary artery and the adjacent vessels [17,18] (Figure 1). Additionally, it provides a guidance for the appropriate angiographic projections during cardiac catheterization.

3.3. Management of the Prostaglandin E1 (PGE1)

Neonates in whom the DAs are maintained open by PGE1 infusion, ductal constriction should be reevaluated by TTE 4−6 h before the procedure. If the ductal waist is larger than 3 mm, PGE1 should be reduced to a minimum dose or discontinued with the aim to maintain the oxygen saturation around 75–80% and the ductal waist of 2.5–3 mm. It is mandatory to confirm that the DA is properly constricted before starting the procedure. Otherwise, there would be a high risk of stent migration.

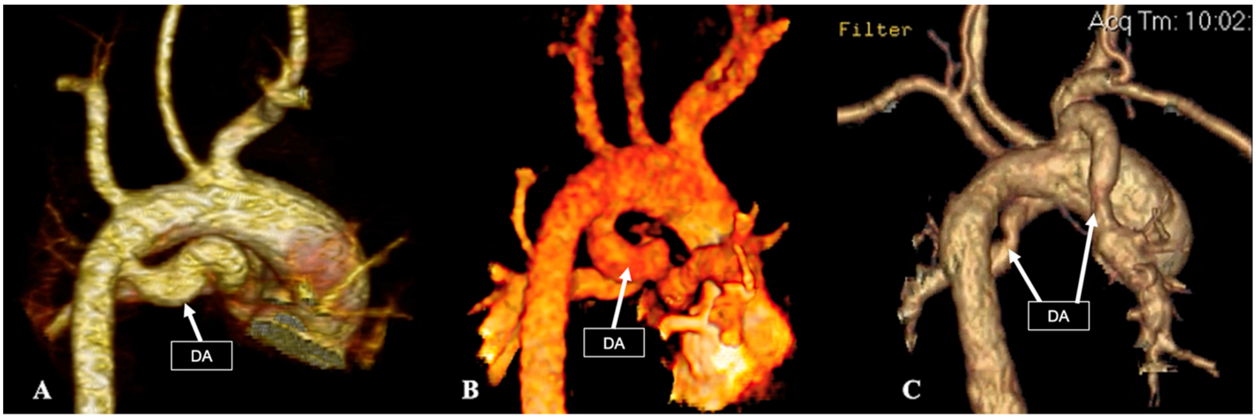

Figure 1. Three-dimensional cardiac computed tomography in different origins of the ductus arteriosus (DA). (**A**) Originated from the proximal descending aorta. (**B**) Originated from the aortic arch. (**C**) Originated from the aortic branches. Pictures, courtesy of Phuoc Duong, MD. Paediatric Cardiologist, Alder Hey Children's Hospital, Liverpool, The UK.

3.4. Antiplatelet Therapy

At the moment, there is no universally accepted antiplatelet treatment protocol for the DS. Nonetheless, as is routine practice in adult coronary interventions, it is reasonable to start antiplatelet drug(s), such as aspirin and/or clopidogrel, a day before the procedure, to minimize the possibility of acute stent thrombosis.

3.5. Ductal Stenting Procedure

Ductal stenting is a procedure with one of the highest risks for morbidity and mortality in neonates. Therefore, decision making should be performed on the basis of surgical agreement and full back up by the team. The operator and the team should take care of all the treatment details in order to minimize the risk and maximize the chance of success. It should be performed in the neutral thermal environment under general anesthesia. Vascular access should be obtained under ultrasound guidance in the planned position with 5F or 6F thin wall introducer sheath (Glidesheath Slender®: Terumo, Tokyo, Japan). Heparin 50–100 U/kg should be administered in order to maintain ACT > 250 s. Subsequently, selective angiograms are performed in the appropriate positions, when the catheter engages the origin of the DA, and are crucial to profile the ductal anatomy. In general, the pulmonary artery (PA) bifurcation and the proximal branch stenosis can be well identified in the 4-chamber (LAO 25–30°, cranial 25–30° for levocardia and RAO equivalent for dextrocardia) and the straight lateral projections [19]. All the measurements (the ductal waist, most dilated ductal diameter, ductal length, proximal and distal PA branch diameters) are then re-evaluated in both projections.

3.6. The Instruments

The Judkins Right (JR) diagnostic and guide catheters and the low tip load (0.5–0.7 g) moderate support hydrophilic coronary angioplasty guidewires (CAG) (i.e., Hi-Torque Whisper Extra Support: Abbott Vascular, Santa Clara, CA, USA) are standard workhorses for engaging the straight DA. However, for the tortuous DA or acutely angulated ductal ampulla, introducing the CAG through the custom-made cut pigtail catheter or telescoping the JR catheter with the microcatheter (i.e., Progreat® microcatheter system: Terumo, Tokyo, Japan) are useful methods for crossing the DA. Additionally, for the tortuous DA, the high support CAG (i.e., Hi-Torque Iron Man Extra Support: Abbott Vascular, Santa Clara, CA, USA) is a useful tool to straighten the DA for precise length measurement and to facilitate introduction of the stent. Lastly, the CAG for chronic total occlusion (i.e., Conquest Pro 12: Asahi Intecc, Seto, Japan) is an essential instrument for recanalizing the thrombosed or closed DA.

Stents and balloon catheters are also the essential instruments. To comply with the variation of the DA morphology, the diameters of the stents available on the shelf should include 3.5 mm, 4 mm, and 4.5 mm, whilst the lengths should range from 8 mm to 20 mm. Balloon catheters are useful tools for stent post-dilation and proximal pulmonary artery angioplasty. Moreover, they can be used to interrogate the length of the duct precisely. The essential diameters and lengths are 2.5–4.5 mm and 8–20 mm, respectively. The essential instruments have been listed in Table 1.

Table 1. Instruments for ductal stenting.

Catheters - 4F Judkins Right (JR) - 5F Heartrail^{TM} II JR guiding (Terumo) - 4–5F Pigtail (may need to be cut) - Progreat®micro catheter (Terumo)
0.014″ Coronary guide wires - Hydrophilic (to cross the DA): Whisper ES (Abbott) - Extra-support (to straighten the duct, introduce the stent): Ironman (Abbott) - Chronic total occlusion (to recanalize the DA): Cross-it (Abbott), Conquest Pro12 (Asahi)
Coronary stents - Diameter 3.5, 4.0, 4.5 mm - Length 8–20 mm
Coronary balloon catheters (for length measurement and strut dilation) - Diameter: 2.5–4.5 mm - Length: 8–20 mm

3.7. Vascular Access

The DA in patients with duct-dependent pulmonary circulation may originate from the descending aorta, the underside of the aortic arch, the subclavian artery, the innominate artery, and the ascending aorta. Correct vascular access site facilitates the procedure and minimizes the risk of complications. In practice, the DA should be approached from the nearest and straightest vascular entry site. (Figure 2) Access from the femoral artery is suitable for the DA, which arises from the proximal descending aorta. Similarly, it is a straightforward approach from the groin (femoral artery or vein (presence of an interventricular connection)) or umbilical artery when the DA arises from the innominate artery, subclavian artery, or ascending aorta. Carotid or axillary artery approach is useful when the DA arises from the underside of the aortic arch. Recent studies have shown that percutaneous carotid artery access has a low rate of vascular complications, with preserved vascular patency on follow-up, and no neurological sequelae [20–22].

3.8. The Straight Ductus Arteriosus

The straight DA, with a wide proximal ampulla tapering down to a constricted pulmonary end, mostly originates from the proximal descending aorta and may also be found originating from the aortic branches. Occasionally, vertical DA from the aortic arch can be straight and short. The DA is clearly demonstrated by aortograms near the ductal origin in the 4-chamber and straight lateral projections. The DA is likely to be crossed with ease by advancing a conventional 0.014″ low tip load with moderate support CAG (Figure 3). However, the DA with the tight constriction and short tortuosity (or acute bend) of the distal pulmonary end can be very challenging when trying to pass the guidewire into the pulmonary artery. When faced with this challenge, advancing the guide catheter close to the ductal ampulla to telescope the system with a microcatheter can be a helpful method to facilitate crossing and further support for stent placement. Repeated hand injections of small volume of contrast are made through a Y-adaptor of the guiding catheter for ductal measurements. In most cases, the dimensions of the DA can be measured accurately in the straight lateral projection, when it originates from the descending aorta and in the 4-chamber projection, when it arises from the aortic branches. The stent diameter should be selected according to the patient body weight, as previously described. The stent should cover 1–2 mm beyond the pulmonary artery end of the DA and should not protrude beyond superior rim of aortic ampulla of the DA. Stents protruding into the aorta may obstruct the aortic flow and cause difficulty to re-cross for follow-up catheter re-interventions. With commercially available pre-mounted coronary stents nowadays, the stent foreshortening is less than 1% upon full expansion [23]. Therefore, selected stent length can be the same length as the DA, measured angiographically. As the stent is advanced to the landing position, adjustment of the stent position should be confirmed by frequent hand injections of the contrast media in the same fluoroscopic projections. Once the stent position is acceptable, initially, the assistant should inflate the balloon slowly to create a dog bone shape of the balloon, allowing the operator to make final adjustments of position. Subsequently, the balloon can be inflated rapidly, whilst the operator keeps the system fixed, as the stent may tend to move forward. After full inflation to its nominal pressure, the balloon should be deflated completely and angiograms are repeated to assess stent position and its patency, any residual uncovered constriction, and stenosis of the pulmonary artery branches. Additional stent(s) placement, post-dilation to improve stent expansion, or dilation of pulmonary artery branch can be performed with the wire still across the DA. Finally, the guidewire and the catheter can be removed.

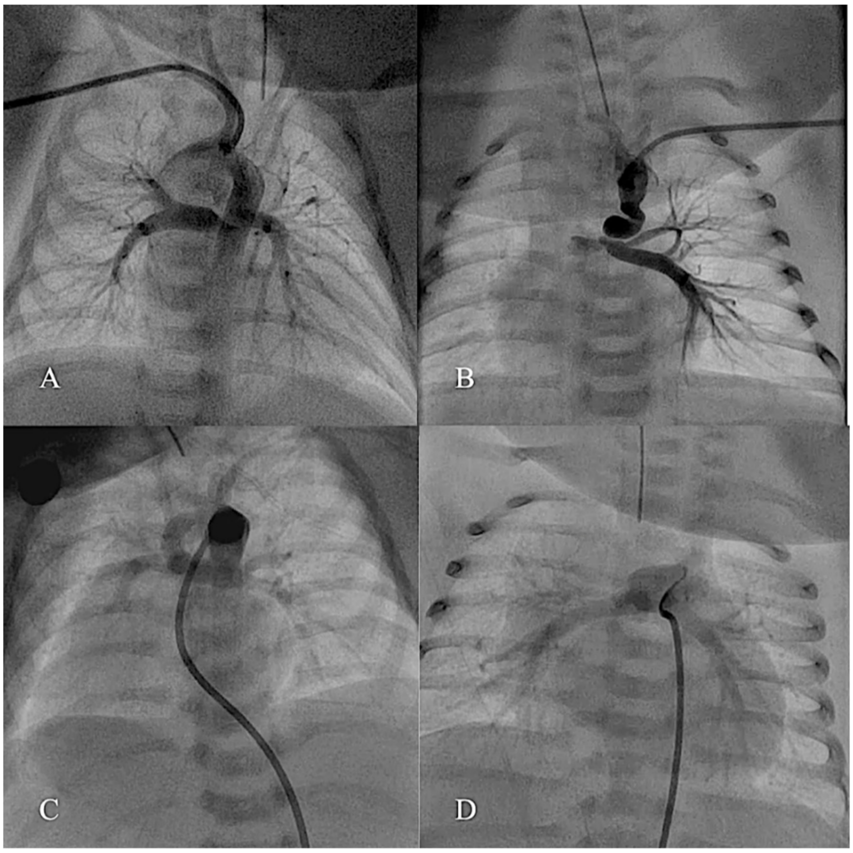

Figure 2. Different approaches for ductal stenting. (**A**) From right axillary artery. (**B**) From left axillary artery. (**C**) From femoral vein to ascending aorta. (**D**) From femoral artery.

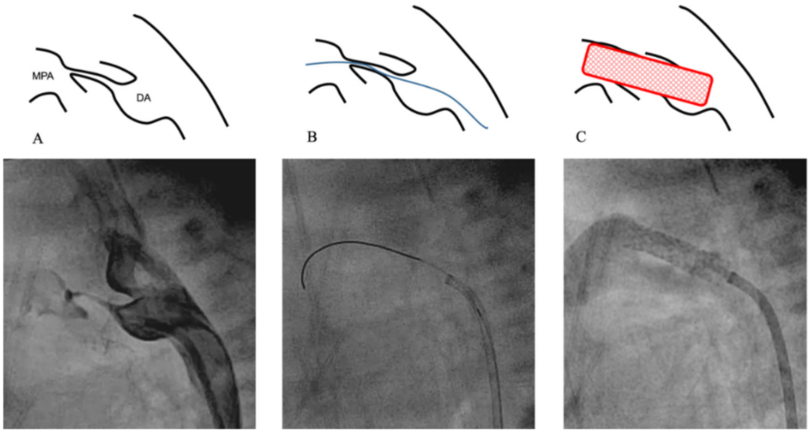

Figure 3. Lateral projection of the ductus arteriosus (DA) arising from proximal descending aorta and stenting procedure. (**A**) Selective ductal angiography demonstrated tightly constricted pulmonary artery end of the DA. (**B**) 0.014″ coronary guidewire crossed the DA. (**C**) Stent covered entire length of the DA. MPA: Main pulmonary artery.

3.9. The Tortuous Ductus Arteriosus

Increased ductal tortuosity is a predictor for procedural failure, pulmonary artery jailing, and unintended reintervention [5,9,13,24,25]. Recent publications have defined the complexity of ductal tortuosity by using the distinct equations between the total ductal length and straight length, as ductal tortuosity index (DTI) ((total ductal length/straight length − 1) × 100) [17] or curvature index (CI) (total ductal length − straight length/total ductal length) [9]. Until now, although there was no definite cut point to predict feasibility of ductal stenting in tortuous DA, higher DTI or CI represent greater ductal complexity, which can be deemed to be unsuitable for stenting, even by experienced operators. As a personal preference, a DA with more than 2 curves is not practical to attempt DS. The procedural steps of tortuous DA stenting has been described in Figure 4.

Technical challenges of ductal stenting in the tortuous DA include difficulty in ductal crossing, inaccurate measurement of ductal length, and non-uniform change of ductal configuration after stretching with the guidewire and the stent. The origin, the shape, the length, and the insertion point of the DA should be assessed in the most unforeshortened projection, so that the appropriate diameter and length of the stent can be selected. Aortogram in 4-chamber and straight lateral projections can provide ductal details in most cases. However, these standard angulations may not be suitable in some complex DAs. Proper projections can be planned with guidance from pre-procedural 3-dimensional volume-rendered CCT.

For successful crossing of the tortuous DA, it is important to keep the guiding catheter close to the ductal ampulla for coaxial alignment and to maximize support. Nevertheless, the operator should avoid "deep seating" of the catheter into the DA, since it may cause ductal dissection or perforation. Conventional 0.014″ low tip load, hydrophilic coated with moderate support CAG is a workhorse guidewire for tortuous DA. However, the operator should shape the tip of the guidewire (primary curve) to match the most angulated curve of the DA and shape, just proximal to the first bend (secondary curve) to match with the size of the DA. In order to avoid ductal injury, the guidewire is introduced by slow continuous spinning–advancing and never forceful advance in the DA when the tip is bent. Occasionally, it requires telescoping the system through a microcatheter for ductal crossing and wire stabilization. Once the wire has crossed the duct, it is reasonable to keep the tip of the guidewire in either the left or right lower PA. In addition, allowing the tip of the guidewire to buckle before advancing deep into distal PA is a practical technique to avoid distal end perforation, which may lead to acute pulmonary hemorrhage. Once the guidewire is securely placed, the DA tends to be stretched and may cause desaturation. In cases that require more support, the operator may add additional guidewire into ipsilateral or contralateral PA branch (buddy wire) or exchange the conventional guidewire with the stiff guidewire over the microcatheter.

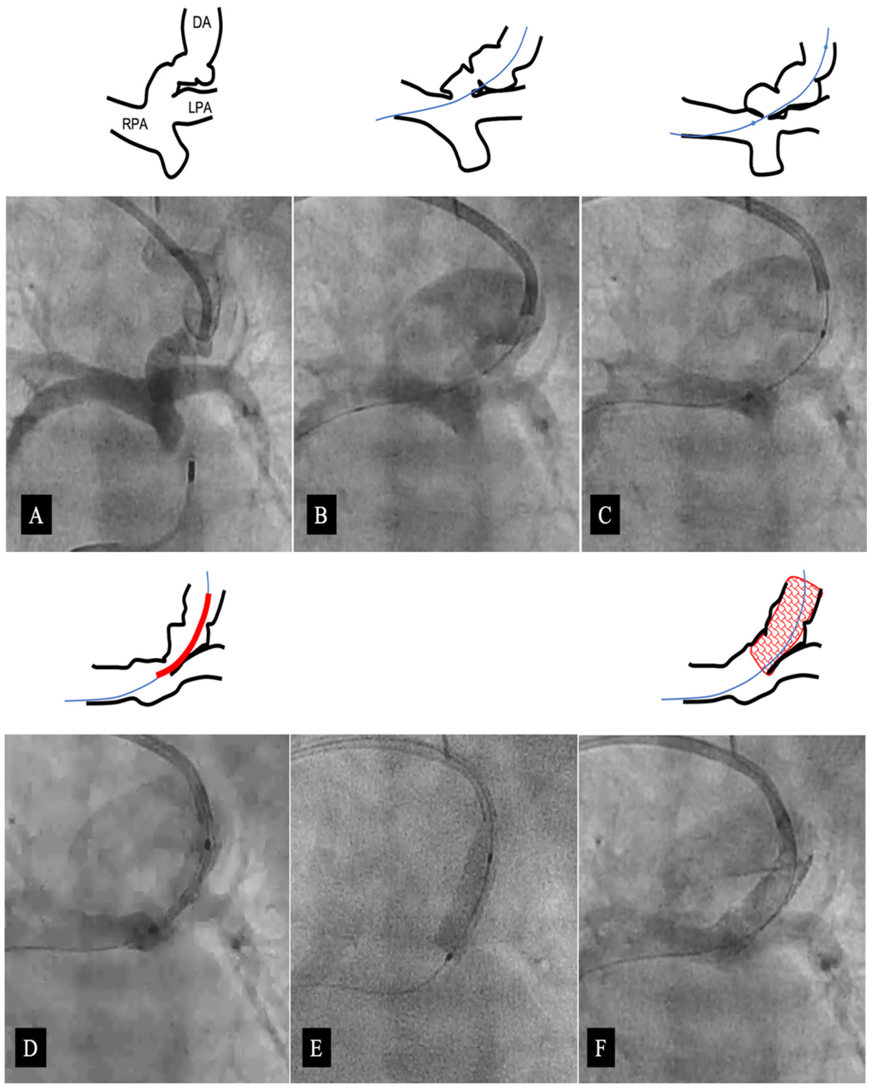

Figure 4. Stenting of a tortuous vertical ductus arteriosus (DA). (**A**) Selective arch aortogram near origin of the DA. (**B**) Repeated selective angiogram after placing the guidewire in the right PA demonstrated stretching of the DA. (**C**) Length interrogation was performed with markers of the coronary balloon catheter (without inflation). (**D**) Introducing the stent with the same length of the previous balloon catheter. (**E**) Inflation of the stent at its nominal pressure. (**F**) Final angiogram showed satisfactory stent position with unobstructed flow to both PAs. RPA: Right pulmonary artery, LPA: Left pulmonary artery.

Measurement of the precise landing zone length is quite challenging in the DA with multiple curves. Pre-procedural CCT dataset can be reformatted using curved multi-planar reconstruction (MPR) technique to allow the center-line of the arterial duct to be displayed in linear fashion, which is a useful technique to measure the exact ductal length before the procedure. However, the length should be reconfirmed, when the DA has been stretched with the guidewire. Using the rapid-exchange coronary balloon catheter with 2 markers, with the length that matches the intended landing zone, is a practical way to interrogate the length. Repeat angiograms in bi-plane projections through the guiding catheter with the balloon catheter in the DA will provide the final information for selection of the stent length. Similar to the straight DA, without associated pulmonary coarctation, the stent should cover 1–2 mm distal to the pulmonary artery end of the duct and extend only

1–2 mm beyond ductal ampulla. In most cases, pre-dilation of the constricted duct with smaller balloon diameter before stenting is not necessary. In fact, pre-dilation may induce ductal spasm, thrombosis, and dissection which may further complicate the procedure.

Recent designs of the coronary stents have good trackability and good ability to conform with curved vessel after implantation. Therefore, when the guiding catheter is coaxially aligned and the guidewire is adequately supported, choosing a single long stent that covers the entire duct is more preferable than selecting short multiple stents for implantation. Wriggling of the guidewire can also be used to facilitate the passage of the stent by optimizing the coaxial push. Once the stent position is satisfactory, it should be implanted in similar fashion as in the straight DA. The operator must pay more attention to stabilizing the system as the stent tends to jump forward often. Removing the balloon should be done carefully to avoid dislodgement of the implanted stent. Additionally, it is crucial to deflate the balloon completely and negotiate the balloon-guidewire gently, when withdrawing the balloon into the guiding catheter. Finally, repeat hand injections for angiograms before and after guidewire removal should be routinely performed, since the shape, angulation, and perfusion of the stent may change.

3.10. The Ductus Arteriosus with Pulmonary Artery Coarctation

In pulmonary atresia with ventricular septal defect (PA/VSD) or other forms of pulmonary atresia with right isomerism complex or univentricular cardiac physiology, the DA morphology is often tortuous and originates vertically from the underside of the aorta. Additionally, they have a tendency to insert onto the proximal pulmonary artery (left pulmonary artery in left aortic arch), causing a significant constriction and distortion of the proximal PA.

When there is unilateral stenosis of the proximal PA, the guidewire should be probed into the stenosed PA and stent can be deployed to cover the entire segment of pulmonary coarctation and the DA. By doing so, the contralateral PA will be intentionally jailed by the implanted stent. In most cases, the flow into the jailed PA is not compromised since most coronary stents are currently open cell designs. However, if the flow through the contralateral PA is limited, it can be subsequently wired for post-dilation. In order to avoid stent distortion or fracture, it is important to use the balloon catheter with the diameter of the distal PA branch, but not exceed 60% of the diameter of the freshly implanted stent.

When there are bilateral PA stenoses (Figure 5), it is useful to wire both PAs and measure the potential landing zone that covers the entire pulmonary coarctation and the DA. Although there is no specific rule to select the major PA branch for stent implantation, the less angulated one is usually preferable. At this stage, some experienced operators may pre-dilate the minor PA branch by a balloon catheter of a diameter similar to the diameter of the distal vessel to minimize the risk of complete PA branch obstruction after stent placement. Subsequently, after removing the guidewire from the minor PA branch, the stent is placed at the intended place. Hand injections should be frequently performed to position the stent precisely and to interrogate the flow through both PA branches clearly. If stenosis at the minor PA branch persists after stent implantation, it should be rewired and post-dilated through the stent struts, as described previously. Another technique, which is more challenging, to deal with bilateral pulmonary coarctation is to deploy the stent just proximal to the pulmonary artery bifurcation. (Figure 6) Then, if necessary, post-dilate both PA branches with kissing balloons. This technique may reduce embedding of the stent into the PA tissue, but it may increase the risk of stent dislodgement/migration, especially when dealing with the short-curved DA.

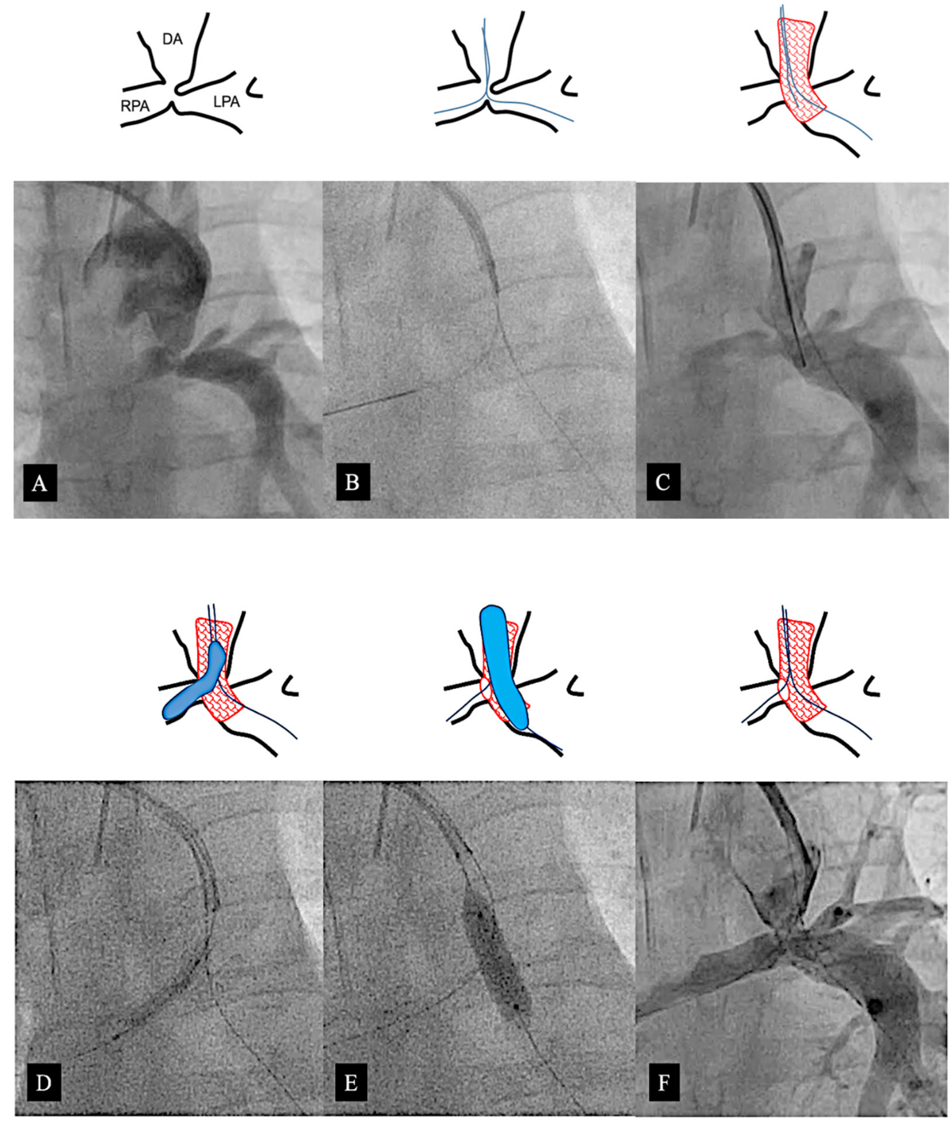

Figure 5. Stenting of vertical ductus arteriosus (DA) associated with bilateral proximal pulmonary artery branch stenosis, small right PA, and large ductal ampulla. (**A**) Selective hand injection of the DA in frontal projection. (**B**) Two buddy wires were placed in the left and right PA for planning of the ductal stenting. (**C**) In this case, due to straighter course of the left guidewire with more stenosis of the left PA origin, the stent was placed from the DA to cover proximal part of the left PA with intention to jail the right PA ostium. Thereafter, the right PA was re-crossed with the microcatheter system. (**D**) The stent strut and the proximal right PA was then dilated to improve flow to the right lung. (**E**) Subsequently, the whole stent was re-dilated for proper apposition to the vessel wall. (**F**) Selective angiogram after stenting demonstrated adequate flow through both pulmonary arteries. RPA: Right pulmonary artery, LPA: Left pulmonary artery.

3.11. The Bilateral Ductus Arteriosus

These types of bilateral DAs usually supply disconnected central branch pulmonary arteries. The DA may arise from the inner curvature of the aortic arch, the innominate or the subclavian artery to an ipsilateral pulmonary artery. Stenting of the DA can be achieved with the same principles and methods, as mentioned earlier. (Figure 7) However, due to single lung supply, the stent diameter should be 0.5–1 mm smaller than the recommended size [11].

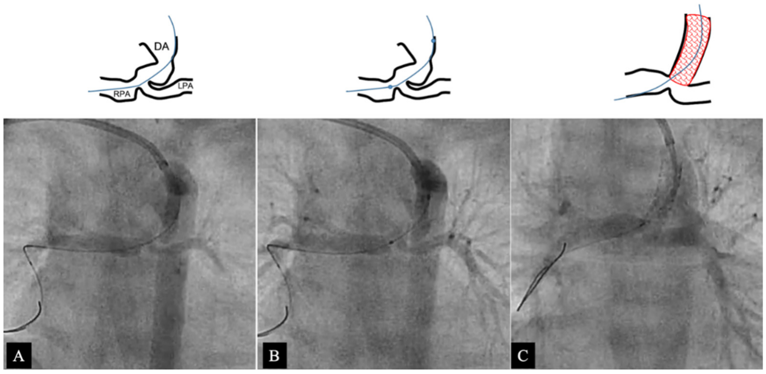

Figure 6. Stenting of vertical ductus arteriosus (DA) associated with bilateral proximal pulmonary artery branch stenosis and hypoplastic left PA. (**A**) Selective hand injection of the ductus in cranial projection after the guidewire placed at the right lower PA. (**B**) Length interrogation was performed with coronary balloon catheter, 2.5 × 15 mm. (**C**) Stent was placed just proximal to the PA bifurcation. The underfilled left PA immediately increased in size after stenting. RPA: Right pulmonary artery, LPA: Left pulmonary artery.

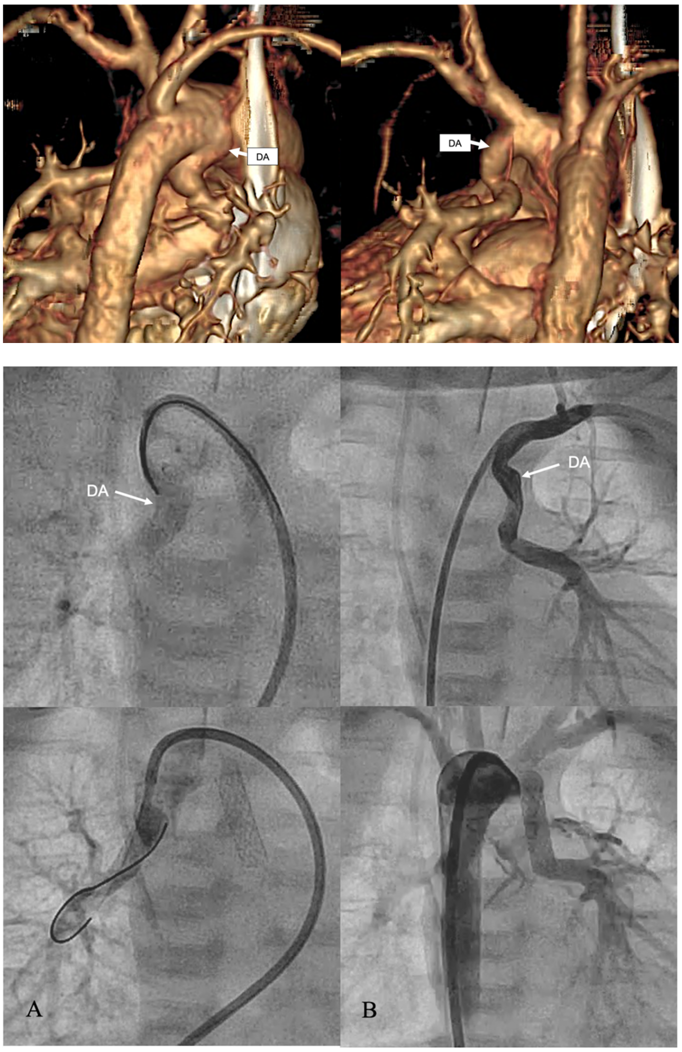

Figure 7. Three-dimensional volume rendering of the computed cardiac tomography (CCT) demonstrated right aortic arch with bilateral ductus arteriosus (DA). One is from the aortic arch to supply the right PA, another one is from the innominate artery to the left lung. Both DAs were successfully stented. (**A**,**B**).

4. Dealing with Early Complications

4.1. Stent Thrombosis

This can be a catastrophic complication, which can occur acutely (within 24 h), subacutely (within 30 days), or late (≥30 days) after stent implantation with a variable rate of between 0.8% and 25% from previous publications [10,26–28]. Unfortunately, at this stage, there is no clear evidence to identify the causes of this complication. Extrapolating from percutaneous coronary interventions, the mechanisms underlying stent thrombosis are likely to be multifactorial, which include patient-related factors (complex patients and lesions), procedural factors (stent choice, multiple stents usage, stent-vessel wall apposition), and postprocedural factors (type and duration of antiplatelet therapy) [29]. In our practice, it is usual to start oral antiplatelet dose of aspirin 24 h before the procedure, maintain activated clotting time >250 s throughout the procedure, and infuse heparin of 15–20 U/kg/hr for 24–48 h to prevent acute stent thrombosis. Starting dual-antiplatelet therapy (DAPT) after the procedure and continuing them for at least 6 months before switching to 3–5 mg/kg/day of oral aspirin until the next surgical intervention are also our routine practices to prevent subacute and late stent thrombosis.

If stent thrombosis occurs during the procedure, the DA should be rewired for balloon dilation with 0.5–1 mm larger than the stent diameter to break up the thrombus and mitigate against the risk of stent under-expansion. Local infusion of streptokinase or altepase should be given simultaneously. New stent implantation may be helpful if earlier methods fail to prevent thrombus. Adjunctive use of the thrombectomy devices may not be applicable in the newborns due to the risk of massive blood loss during thrombus aspiration. If stent thrombosis occurs after the procedure, revascularization is more challenging with less chance of success. Chronic total occlusion (CTO) guidewire is a useful tool to drill through the organized thrombus for further treatments, as described earlier.

4.2. Stent Migration

Stent migration may occur with a rate of 0.9–2.8% [5,7], which is usually related to the tortuous, short, or less constricted DAs. Although the patient, who encounters this complication, is usually hemodynamically stable, successful retrieval and re-deploying the migrated stent are rare [30]. Therefore, surgical removal of the migrated stent is required in most cases [31].

The operator should pay attention to each procedural step in order to avoid this complication, starting from stent selection, positioning-deploying of the stent, removing of the balloon catheter, and re-manipulating through freshly implanted stent. Once the stent is positioned in the correct landing zone, before inflating the balloon, it is important to withdraw the guiding catheter away from the proximal shaft of the balloon completely. Without doing so, the stent can migrate distally during inflation. Thereafter, it is also important to deflate the balloon fully before withdrawing it back into the guiding catheter. Occasionally, the operator may have to negotiate the whole system by pushing and pulling the guidewire, whilst withdrawing the balloon catheter, to prevent stent entanglement. When an additional stent needs to be implanted, especially in the curved DA, the stent should be gently introduced through the guiding catheter that is placed distal to the first stent. Without proper covering, the second stent may catch and push the first stent distally during its passage.

4.3. Pulmonary Over-Circulation

Suitable oxygen saturation after ductal stenting should be approximately 85–90%. Higher ductal shunting after the procedure may cause pulmonary over-circulation and/or significant diastolic run-off that may lead to coronary and systemic hypoperfusion. Intravenous inotropic support and diuretics may improve the symptoms. Nonetheless, for the patients with failure of medical treatments, implantation of the additional stent [32] as a flow restrictor may improve this problem.

4.4. Pulmonary Under-Circulation

Apart from stent thrombosis or inadequate stent size, pulmonary hypoperfusion can occur when (1) the ductal tissue is not entirely covered, leading to ductal constriction, and (2) the pulmonary artery is additionally jailed by stent migration. However, before considering re-intervention, it is important to provide adequate oxygenation/ventilation, intravascular volume, hemoglobin, and cardiac output. If desaturation persists, comprehensive echocardiographic examination is essential to assess discrete ductal constriction, stent occlusion, or jailing of the pulmonary artery.

4.5. Post-Procedural Care

After the procedure, the patient should be transferred to the neonatal intensive care unit for close monitoring with arterial and central venous lines. The patient can be extubated once hemodynamic and neurologic conditions are stable. Heparin and anti-platelets should be given as previously mentioned. Close follow-up, especially at 3–6 months after the procedure, is recommended since the risk of re-intervention is high during this period [6].

5. Conclusions

Ductal stenting is an effective alternative procedure to palliate the patients with duct-dependent pulmonary circulation. However, it requires comprehensive planning, proper catheter laboratory environment/instruments, skillful and careful operators, and seamless teamwork to make this procedure safe and successful.

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References

1. Gibbs, J.L.; Rothman, M.T.; Rees, M.R.; Parsons, J.M.; Blackburn, M.E.; Ruiz, C.E. Stenting of the arterial duct: A new ap-proach to palliation for pulmonary atresia. *Br. Heart J.* **1992**, *67*, 240–245. [CrossRef] [PubMed]
2. Alsagheir, A.; Koziarz, A.; Makhdoum, A.; Contreras, J.; Alraddadi, H.; Abdalla, T.; Benson, L.; Chaturvedi, R.R.; Honjo, O. Duct stenting versus modified Blalock-Taussig shunt in neonates and infants with duct-dependent pulmonary blood flow: A systematic review and meta-analysis. *J. Thorac. Cardiovasc. Surg.* **2021**, *161*, 379–390.e8. [CrossRef] [PubMed]
3. Bentham, J.R.; Zava, N.K.; Harrison, W.J.; Shauq, A.; Kalantre, A.; Derrick, G.; Chen, R.H.; Dhillon, R.; Taliotis, D.; Kang, S.L.; et al. Duct Stenting Versus Modified Blalock-Taussig Shunt in Neonates With Duct-Dependent Pulmonary Blood Flow: Associations With Clinical Outcomes in a Multicenter National Study. *Circulation* **2018**, *137*, 581–588. [CrossRef]
4. Li, D.; Zhou, X.; Li, M. Arterial duct stent versus surgical shunt for patients with duct-dependent pulmonary circulation: A meta-analysis. *BMC Cardiovasc. Disord.* **2021**, *21*, 9. [CrossRef] [PubMed]
5. Udink Ten Cate, F.E.; Sreeram, N.; Hamza, H.; Agha, H.; Rosenthal, E.; Qureshi, S.A. Stenting the arterial duct in neonates and infants with congenital heart disease and duct-dependent pulmonary blood flow: A multicenter experience of an evolv-ing therapy over 18 years. *Catheter Cardiovasc. Interv.* **2013**, *82*, E233–E243. [CrossRef]
6. Glatz, A.C.; Petit, C.J.; Goldstein, B.H.; Kelleman, M.S.; McCracken, C.E.; McDonnell, A.; Buckey, T.; Mascio, C.E.; Shashidharan, S.; Ligon, R.A.; et al. Comparison between Patent Ductus Arteriosus Stent and Modified Blalock-Taussig Shunt as Palliation for Infants with Ductal-Dependent Pulmonary Blood Flow: Insights from the Congenital Catheterization Research Collaborative. *Circulation* **2018**, *137*, 589–601. [CrossRef]

7. Boucek, D.M.; Qureshi, A.M.; Goldstein, B.H.; Petit, C.J. Blalock-Taussig shunt versus patent ductus arteriosus stent as first palliation for ductal-dependent pulmonary circulation lesions: A review of the literature. *Congenit. Heart Dis.* **2019**, *14*, 105–109. [CrossRef]
8. Celebi, A.; Yucel, I.K.; Bulut, M.O.; Kucuk, M.; Balli, S. Stenting of the ductus arteriosus in infants with functionally univentricular heart disease and ductal-dependent pulmonary blood flow: A single-center experience. *Catheter. Cardiovasc. Interv.* **2017**, *89*, 699–708. [CrossRef]
9. Qureshi, A.M.; Goldstein, B.H.; Glatz, A.C.; Agrawal, H.; Aggarwal, V.; Ligon, R.A.; McCracken, C.; McDonnell, A.; Buckey, T.M.; Whiteside, W.; et al. Classification scheme for ductal morphology in cyanotic patients with ductal dependent pulmonary blood flow and association with outcomes of patent ductus arteriosus stenting. *Catheter. Cardiovasc. Interv.* **2019**, *93*, 933–943. [CrossRef]
10. Roggen, M.; Cools, B.; Brown, S.; Boshoff, D.; Heying, R.; Eyskens, B.; Gewillig, M. Can ductus arteriosus morphology influ-ence technique/outcome of stent treatment? *Catheter. Cardiovasc. Interv.* **2020**, *95*, 1149–1157. [CrossRef] [PubMed]
11. Alwi, M.; Choo, K.K.; Latiff, H.A.; Kandavello, G.; Samion, H.; Mulyadi, M.D. Initial results and medium-term follow-up of stent implantation of patent ductus arteriosus in duct-dependent pulmonary circulation. *J. Am. Coll. Cardiol.* **2004**, *44*, 438–445. [CrossRef] [PubMed]
12. Schneider, M.; Zartner, P.; Sidiropoulos, A.; Konertz, W.; Hausdorf, G. Stent implantation of the arterial duct in newborns with duct-dependent circulation. *Eur. Heart J.* **1998**, *19*, 1401–1409. [CrossRef]
13. Santoro, G.; Gaio, G.; Palladino, M.T.; Iacono, C.; Carrozza, M.; Esposito, R.; Russo, M.G.; Caianiello, G.; Calabrò, R. Stenting of the arterial duct in newborns with duct-dependent pulmonary circulation. *Heart* **2008**, *94*, 925–929. [CrossRef] [PubMed]
14. Aggarwal, V.; Dhillon, G.S.; Penny, D.J.; Gowda, S.T.; Qureshi, A.M. Drug-Eluting Stents Compared With Bare Metal Stents for Stenting the Ductus Arteriosus in Infants With Ductal-Dependent Pulmonary Blood Flow. *Am. J. Cardiol.* **2019**, *124*, 952–959. [CrossRef] [PubMed]
15. Sivakumar, K.; Pavithran, S.; Sonawane, B.; Rajendran, M.; Ramasamy, R. Serum Sirolimus Levels After Implantation of Third Generation Drug Eluting Cobalt Chromium Coronary Stent in Ductus Arteriosus in Neonates with Duct-Dependent Pulmonary Circulation. *Pediatr. Cardiol.* **2020**, *41*, 1354–1362. [CrossRef]
16. Lee, K.J.; Seto, W.; Benson, L.; Chaturvedi, R.R. Pharmacokinetics of sirolimus-eluting stents implanted in the neonatal arteri-al duct. *Circ. Cardiovasc. Interv.* **2015**, *8*, e002233. [CrossRef]
17. Chamberlain, R.C.; Ezekian, J.E.; Sturgeon, G.M.; Barker, P.C.A.; Hill, K.D.; Fleming, G.A. Preprocedural three-dimensional planning aids in transcatheter ductal stent placement: A single-center experience. *Catheter. Cardiovasc. Interv.* **2020**, *95*, 1141–1148. [CrossRef]
18. Jadhav, S.P.; Aggarwal, V.; Masand, P.M.; Diaz, E.; Zhang, W.; Qureshi, A.M. Correlation of ductus arteriosus length and morphology between computed tomographic angiography and catheter angiography and their relation to ductal stent length. *Pediatr. Radiol.* **2020**, *50*, 800–809. [CrossRef]
19. Alwi, M. Stenting the ductus arteriosus: Case selection, technique and possible complications. *Ann. Pediatr. Cardiol.* **2008**, 38–45. [CrossRef] [PubMed]
20. Choudhry, S.; Balzer, D.; Murphy, J.; Nicolas, R.; Shahanavaz, S. Percutaneous carotid artery access in infants < 3 months of age. *Catheter. Cardiovasc. Interv.* **2016**, *87*, 757–761. [CrossRef]
21. Justino, H.; Petit, C.J. Percutaneous Common Carotid Artery Access for Pediatric Interventional Cardiac Catheterization. *Circ. Cardiovasc. Interv.* **2016**, *9*, e003003. [CrossRef] [PubMed]
22. Polat, T.B. Use of percutaneous carotid artery access for performing pediatric cardiac interventions: Single-center study. *Ann. Pediatr. Cardiol.* **2020**, *13*, 16–24. [CrossRef] [PubMed]
23. Kim, D.B.; Choi, H.; Joo, S.M.; Kim, H.K.; Shin, J.H.; Hwang, M.H.; Choi, J.; Kim, D.G.; Lee, K.H.; Lim, C.H.; et al. A com-parative reliability and performance study of different stent designs in terms of mechanical properties: Foreshortening, recoil, radial force, and flexibility. *Artif. Organs.* **2013**, *37*, 368–379. [CrossRef] [PubMed]
24. Santoro, G.; Gaio, G.; Castaldi, B.; Palladino, M.T.; Iacono, C.; Russo, M.G.; Calabrò, R. Arterial duct stenting in low-weight newborns with duct-dependent pulmonary circulation. *Catheter. Cardiovasc Interv.* **2011**, *78*, 677–685. [CrossRef]
25. Santoro, G.; Gaio, G.; Giugno, L.; Capogrosso, C.; Palladino, M.T.; Iacono, C.; Caianiello, G.; Russo, M.G. Ten-years, sin-gle-center experience with arterial duct stenting in duct-dependent pulmonary circulation: Early results, learning-curve changes, and mid-term outcome. *Catheter. Cardiovasc Interv.* **2015**, *86*, 249–257. [CrossRef]
26. McMullan, D.M.; Permut, L.C.; Jones, T.K.; Johnston, T.A.; Rubio, A.E. Modified Blalock-Taussig shunt versus ductal stenting for palliation of cardiac lesions with inadequate pulmonary blood flow. *J. Thorac. Cardiovasc. Surg.* **2014**, *147*, 397–401. [CrossRef]
27. Michel-Behnke, I.; Akintuerk, H.; Thul, J.; Hagel, K.; Schranz, D. Stent Implantation in the Ductus Arteriosus for Pulmonary Blood Supply in Congenital Heart Disease. *Catheter. Cardiovasc. Interv.* **2004**, *61*, 242–252. [CrossRef]
28. Amoozgar, H.; Cheriki, S.; Borzoee, M.; Soltani, M.; Ahmadipour, M.; Peiravian, F.; Amirghofran, A. Short-term results of ductus arteriosus stent implantation compared with surgically created shunts. *Pediatr. Cardiol.* **2012**, *33*, 1288–1294. [CrossRef]
29. Kirtane, A.J.; Stone, G.W. How to minimize stent thrombosis. *Circulation* **2011**, *124*, 1283–1287. [CrossRef]
30. Pavithran, S.; Sivakumar, K. Successful retrieval of a migrated neonatal ductal stent and strategies to reposition the expand-ed stent in the duct. *Cardiol. Young.* **2018**, *28*, 1050–1052. [CrossRef]

31. Vida, V.L.; Speggiorin, S.; Maschietto, N.; Padalino, M.A.; Tessari, C.; Biffanti, R.; Cerutti, A.; Milanesi, O.; Stellin, G. Cardiac operations after patent ductus arteriosus stenting in duct-dependent pulmonary circulation. *Ann. Thorac. Surg.* **2010**, *90*, 605–609. [CrossRef] [PubMed]
32. Demir, F.; Cools, B.; Gewillig, M. Flow reduction of a neonatal stented arterial duct by covered coronary stent. *Catheter. Car-diovasc. Interv.* **2015**, *86*, E73–E75. [CrossRef] [PubMed]