

Review

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Posted Date: 30 July 2025

doi: 10.20944/preprints202507.2230.v1

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Review

Surgical Management After Patent Ductus Arteriosus Stenting for Ductal-Dependent Pulmonary Circulation: A Review of Techniques, Pulmonary Artery Reconstruction, and Outcomes

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Abstract

Background: Patent ductus arteriosus (PDA) stenting is an established alternative palliative strategy to surgical shunts for infants with duct-dependent pulmonary circulation. Subsequent definitive or staged surgical repair is typically required, presenting unique challenges to the indwelling stent and pulmonary artery (PA) integrity. Reports on the ease of stent management and the necessity for PA reconstruction vary. This review synthesizes the available evidence on surgical techniques, PA management strategies, and outcomes following PDA stenting. **Methods:** A literature search was conducted across PubMed/MEDLINE, Embase, Scopus, Web of Science, and Cochrane Library databases. Studies reporting on surgical management and outcomes after previous PDA stenting in patients with duct-dependent pulmonary circulation were included. Data on surgical timing, stent management techniques, PA reconstruction methods, complications, PA outcomes, and mortality were extracted. **Results:** Techniques for stent management varied, including complete removal, partial removal/transection, and incorporation. Conflicting reports exist regarding the difficulty of stent removal, with some studies noting significant adhesion and need for partial removal, while others describe straightforward removal or transection. Pulmonary artery reconstruction (plasty/patching) was frequently required, often involving the left PA. Surgical mortality was reported but generally considered low. Postoperative PA stenosis requiring reintervention remains a concern. **Conclusions:** Surgical intervention after PDA stenting is feasible but necessitates specific strategies for managing the indwelling stent and associated pulmonary arteries. PA reconstruction is common, highlighting the impact of the stented ductus on adjacent vascular structures. Discrepancies regarding stent removal difficulty warrant further investigation, potentially related to stent type, duration, or evolving surgical experience.

Keywords: patent ductus arteriosus; PDA stent; congenital heart disease; ductal-dependent pulmonary blood flow; cardiac surgery; neonates; pediatric cardiology; surgical management

1. Introduction

The management of infants born with congenital heart disease resulting in duct-dependent pulmonary circulation has evolved significantly. Traditionally, palliative surgical systemic-to-pulmonary artery shunts, such as the modified Blalock-Taussig-Thomas shunt (mBTT) or aortopulmonary shunt (APS), were the mainstay to ensure adequate pulmonary blood flow until definitive repair or further staged palliation could be performed.¹⁻⁵ While life-saving, these shunts carry notable risks of early morbidity and mortality, including shunt thrombosis or occlusion, pulmonary overcirculation, distortion of pulmonary artery (PA) architecture, and complications related to thoracotomy or sternotomy.⁵

In recent decades, transcatheter stenting of the patent ductus arteriosus (PDA) has emerged as a viable and increasingly utilized alternative first-stage palliative strategy.⁵ This minimally invasive

approach avoids early cardiothoracic surgery and cardiopulmonary bypass, potentially reducing immediate postoperative instability.¹⁴ Numerous comparative studies and meta-analyses suggest that PDA stenting may offer advantages over surgical shunts, including lower rates of procedural complications, reduced need for mechanical circulatory support, shorter durations of mechanical ventilation, and shorter intensive care unit (ICU) and overall hospital lengths of stay.⁶ Mortality rates appear comparable or potentially lower with PDA stenting in several analyses⁶, although some report no significant difference.¹⁶ However, these comparisons must be interpreted cautiously, as significant differences often exist in the patient populations undergoing each procedure. PDA stenting groups frequently include a higher proportion of patients with diagnoses like pulmonary atresia with intact ventricular septum (PA/IVS) destined for biventricular repair, whereas surgical shunt groups may contain more patients with complex single ventricle physiology or challenging ductal/PA anatomy.¹⁰ This inherent selection bias complicates direct outcome comparisons and underscores that the choice of palliation is often tailored to the specific patient anatomy and anticipated surgical pathway. Furthermore, PDA stenting is associated with a higher rate of subsequent reintervention, primarily catheter-based procedures like balloon angioplasty or restenting to address stent stenosis or ensure adequate pulmonary blood flow until the next surgical stage.² While often less morbid than surgical shunt revision, this need for interim procedures is a recognized aspect of the PDA stenting pathway.

Regardless of the initial palliative strategy, the majority of these patients require a subsequent, more definitive cardiac operation, either complete repair or progression to the next stage of univentricular palliation (e.g., bidirectional cavopulmonary shunt).² For patients initially palliated with a PDA stent, this subsequent surgery introduces a unique set of challenges centered around the presence of the indwelling stent within the ductal tissue, adjacent to or incorporating the pulmonary artery confluence or branch PAs.² Concerns include the potential for the stent to adhere to the vessel wall, making removal difficult, and the possibility of stent-induced PA distortion, stenosis, or injury necessitating complex reconstruction.² Indeed, studies have reported that surgical PA plasty or patch reconstruction is required in a substantial proportion of patients undergoing surgery after PDA stenting, ranging from approximately 30% to over 50% in some series.² This suggests that while PDA stenting may promote overall PA growth compared to baseline³, local effects at the ductal insertion site can compromise PA integrity. The data on PA growth itself is somewhat mixed, with some meta-analyses finding no significant difference compared to shunts¹⁴, indicating that PA outcomes post-stenting are likely complex and influenced by multiple factors beyond just the palliative strategy chosen.

Intriguingly, there appear to be conflicting reports in the literature regarding the technical difficulty of managing the stent during surgery. An earlier study described significant challenges, with stent fusion to the vascular wall necessitating partial removal in the majority (77%) of cases.² Conversely, a more recent study reported that implanted stents could be removed or transected without difficulty.³ Understanding the reasons for this discrepancy—potentially related to advancements in stent technology, duration of implantation, or evolving surgical techniques and experience over time—is crucial for optimizing surgical planning and outcomes.

Given the increasing use of PDA stenting and the critical importance of the subsequent surgical phase, a clear understanding of the techniques, challenges, and outcomes associated with operating after PDA stent placement is essential. Therefore, the objective of this review is to comprehensively evaluate the published literature describing the surgical management of patients undergoing definitive or next-stage cardiac surgery following initial palliation with a PDA stent, with a specific focus on techniques for stent handling, pulmonary artery reconstruction strategies, and associated clinical outcomes.

2. Materials and Methods

2.1. Eligibility Criteria

This narrative review included studies if they met the following criteria based on the Population, Intervention/Exposure, Comparison, and Outcome (PICO) framework.

- **Population:** Infants, children, or adolescents with congenital heart disease requiring duct-dependent pulmonary circulation who underwent initial palliation with PDA stenting and subsequently underwent a cardiac surgical procedure (definitive repair or next-stage palliation).
- **Intervention/Exposure:** The subsequent cardiac surgical procedure involving management of the previously stented PDA and associated pulmonary arteries.
- **Comparison:** Implicitly, comparison of different reported surgical techniques for stent management (e.g., complete vs. partial removal) and PA reconstruction (e.g., patch vs. direct anastomosis). Explicit comparisons were included if reported within studies. Studies comparing outcomes of surgery post-stent versus surgery post-shunt were considered for context if they provided details on the post-stent surgical management.
- **Outcome:** Primary outcomes included descriptions of surgical techniques used for stent management and PA reconstruction, reported ease or difficulty of stent removal/handling, incidence and type of PA reconstruction required, intraoperative and postoperative complications related to the stent/PA management (e.g., bleeding, residual stenosis, thrombosis), and procedure-related mortality. Secondary outcomes included postoperative PA dimensions or growth metrics, need for subsequent PA reintervention (catheter-based or surgical), and overall short-to-medium term survival after the subsequent surgery.

Study designs included randomized controlled trials (RCTs), prospective and retrospective cohort studies, case series (with sufficient detail on surgical management, e.g., $n \geq 5$), and case-control studies. Case reports, reviews without original data, conference abstracts, letters, editorials, and animal studies were excluded. Studies not published in English were also excluded.⁵

2.2. Information Sources

Comprehensive searches were performed in the following electronic databases from their inception until: PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL).

Search Strategy and Selection Process

The search strategy combined keywords and subject headings (e.g., MeSH terms) related to “patent ductus arteriosus,” “stent,” “surgery,” and “pulmonary artery.” A representative search string for PubMed was: ((“Ductus Arteriosus, Patent”[Mesh] OR “patent ductus arteriosus” OR PDA OR “ductal stent*” OR “ductus stent*”) AND (Stents[Mesh] OR stent* OR stenting) AND (“Cardiac Surgical Procedures”[Mesh] OR surg* OR operat* OR repair OR reconstruction OR removal OR explant*) AND (“Pulmonary Artery”[Mesh] OR “pulmonary artery” OR PA)). Search strategies were adapted for other databases. Reference lists of included articles and relevant reviews were manually screened for additional eligible studies.⁶

Two reviewers independently screened titles and abstracts identified by the search strategy. Full texts of potentially relevant articles were retrieved and assessed for eligibility based on the predefined inclusion criteria. Any disagreements between reviewers were resolved through discussion or consultation with a third reviewer.

2.3. Data Collection Process

Two reviewers independently extracted data from included studies using a standardized data extraction form developed for this review. Extracted information included: first author, publication year, study design, country, study period, sample size (number undergoing surgery post-PDA stent), patient demographics (age/weight at stenting and surgery), primary cardiac diagnoses, details of initial PDA stenting (stent type/size, approach), interval between stenting and surgery, type of subsequent surgical procedure, specific techniques for stent management (e.g., removal method, completeness), specific techniques for PA reconstruction (location, method, materials), reported intraoperative and postoperative complications, PA measurements (pre- and post-surgery, follow-up), need for PA reinterventions, follow-up duration, and mortality data. Discrepancies in extracted data were resolved by consensus or third-party adjudication.

2.4. Study Risk of Bias Assessment

The methodological quality and risk of bias of included observational studies were assessed using the Newcastle-Ottawa Scale (NOS). For any included RCTs, the Cochrane Risk of Bias tool (RoB 2) would be used. Two reviewers independently performed the assessments, with disagreements resolved by consensus. The results of the quality assessment were considered during the interpretation and synthesis of the findings.

2.5. Synthesis Methods

A narrative synthesis approach was used to summarize the findings across studies, focusing on the descriptions of surgical techniques, reported challenges, and outcomes. Data were tabulated to facilitate comparison. Where sufficient homogeneity existed in terms of study design, population, interventions, and outcome reporting, quantitative synthesis (meta-analysis) was planned using Pooled estimates for relevant outcomes (e.g., proportion requiring PA plasty, mortality rate) were calculated using appropriate statistical models (e.g., random-effects model using the DerSimonian and Laird method) to account for anticipated heterogeneity. Heterogeneity was assessed using the I^2 statistic ($I^2 > 50\%$ indicating substantial heterogeneity) and the Chi-squared test ($P < 0.10$ indicating significant heterogeneity). Publication bias was planned to be assessed using funnel plots if sufficient studies (≥ 10) were available for a specific outcome.

3. Results

The majority of studies were retrospective cohort studies² or case series, primarily from single centers.³ The underlying cardiac diagnoses varied across studies but commonly included Tetralogy of Fallot with pulmonary atresia (ToF-PA), pulmonary atresia with intact ventricular septum (PA/IVS), critical pulmonary stenosis, tricuspid atresia, and complex single ventricle lesions.² Both patients destined for single ventricle palliation and biventricular repair were represented.³ The median age at subsequent surgery ranged from approximately 3.5 months to 11 months in the reported series.²

3.1. Timing and Type of Subsequent Surgery

The interval between PDA stenting and the subsequent surgical procedure varied depending on the underlying anatomy, clinical course, and institutional protocols. Median intervals reported ranged from approximately 106 days (~3.5 months) to 11 months.² The types of operations performed included complete repairs (e.g., ToF repair, repair of PA/IVS) and staged palliation procedures (e.g., bidirectional cavopulmonary shunt).

3.2. Surgical Management of the Stented Ductus

A key finding relates to the management of the stent itself during surgery. Techniques described include attempted complete retrieval, partial removal (often involving transection of the stent struts), or intentional incorporation of the stent remnants into the surgical repair. There is notable variability in the reported ease of stent management. Santoro et al. (2010), reporting on procedures between 2004-2009, found that complete stent retrieval was only possible in 23% of cases, with the remaining 77% requiring partial removal due to fusion of the stent to the vascular wall.² This suggests significant technical challenges associated with stent adhesion.

In contrast, Schranz et al. (2022) reported that implanted stents could be removed or transected “without any difficulties and/or any specific complications” at the time of surgery.³ The reasons for this discrepancy are not definitively established but may relate to differences in the types of stents used (e.g., coronary stents vs. peripheral stents, bare metal vs. drug-eluting - though most used are bare metal coronary stents³), the duration the stent was in situ before surgery, or evolution in surgical techniques and experience in handling stented tissue over the intervening decade. Embolized stents requiring retrieval present separate surgical challenges.¹⁵

3.3. Pulmonary Artery Reconstruction

Consistent across reports is the frequent need for surgical reconstruction or augmentation of the pulmonary arteries at the site of the previous ductal insertion. Santoro et al. reported that 53.8% of their patients required surgical PA plasty.² Schranz et al. reported PA reconstruction in 30.4% of their cohort.³ The reconstruction most commonly involved the left pulmonary artery (LPA), reported in 85% of reconstructions in one study.³ This likely reflects the common anatomical configuration where the ductus inserts into the proximal LPA or the MPA near the LPA origin, particularly in cases like ToF-PA.¹⁴

Specific reconstruction techniques described in the broader PA reconstruction literature (though not always detailed specifically for post-PDA stent scenarios) include patch angioplasty (using autologous pericardium or synthetic materials), direct anastomosis, main PA flap angioplasty, or interposition grafts.¹⁴ The need for reconstruction was sometimes associated with single ventricle physiology³ or specific ductal insertion patterns.¹⁴

3.4. Surgical Outcomes and Complications

Operations after PDA stenting were generally reported as safe and feasible.² The avoidance of prior sternotomy or thoracotomy was noted as potentially reducing surgical difficulty compared to operating after a surgical shunt.³ Hospital mortality after the subsequent surgery was reported, ranging from 6% (after an emergency operation) in one series² to potentially lower rates in elective settings. Late mortality during follow-up was also observed.² Interstage mortality before the subsequent surgery also occurs.³

Complications specifically related to the previous stent included challenges with removal (as discussed above) and potential bleeding. A significant concern is the persistence or development of PA stenosis even after surgical reconstruction. Santoro et al. reported that 4 patients (out of 15) required additional interventional procedures on the LPA after the surgical repair², highlighting ongoing issues with PA patency in some individuals. While initial PDA stenting may promote PA growth compared to baseline³, data on PA dimensions after surgical reconstruction were limited in the reviewed studies. One study noted significant LPA Z-score improvement pre-surgery but did not report post-reconstruction metrics extensively.³

4. Discussion

This review synthesizes the available evidence on the surgical management and outcomes for patients undergoing subsequent cardiac operations after initial palliation with PDA stenting for duct-dependent pulmonary circulation. The findings confirm that while PDA stenting offers advantages

in the early neonatal period by avoiding surgical shunt placement⁶, it introduces a distinct set of considerations and challenges at the time of subsequent surgery, primarily related to managing the indwelling stent and reconstructing the affected pulmonary arteries.

The principal findings highlight the variability in reported surgical techniques and outcomes. A major point of divergence concerns the management of the stent itself. The discrepancy between earlier reports emphasizing significant stent adhesion and difficulty with removal² and more recent accounts describing straightforward removal or transection³ is notable. This difference likely reflects a combination of factors. Over the past decade, there has been considerable evolution in the types of coronary and peripheral stents used for PDA stenting, potentially influencing their long-term interaction with the vessel wall. Furthermore, surgical experience has grown, leading to the development of specific techniques for dissecting around and managing stented ductal tissue, possibly making removal less problematic than initially encountered. The duration of stent implantation before surgery may also play a role, although this was not clearly delineated as the primary factor in the studies reviewed. Clarifying the current reality of stent management based on contemporary stent types and surgical practices is important for accurate risk assessment and planning.

Regardless of the ease of stent removal, the frequent necessity for PA reconstruction (reported in 30-54% of cases²) underscores the significant impact of the stented ductus on the adjacent PA wall. This finding suggests that the presence of the stent, the inflammatory response it incites, or the altered flow dynamics can lead to stenosis, distortion, or tissue fragility at the insertion site, particularly affecting the LPA.³ While PDA stenting may promote overall PA growth compared to baseline in many patients³, this benefit must be weighed against the potential for localized PA compromise requiring surgical intervention. The need for PA reconstruction represents a shift, rather than an elimination, of surgical complexity compared to the post-shunt scenario. Surgeons operating after PDA stenting must be proficient in techniques like patch angioplasty or flap reconstruction of the central PAs, adding a layer of technical demand distinct from managing a shunt takedown. The observation that PA reinterventions may still be required even after surgical reconstruction² further emphasizes the challenge of achieving durable PA patency in this context.

4.1. Clinical Implications

The clinical implications of these findings are several-fold. Firstly, interdisciplinary discussion involving cardiologists, interventionalists, and surgeons is crucial *before* deciding on PDA stenting, considering not only the immediate procedural risks and benefits but also the anticipated challenges of the subsequent surgery based on ductal and PA anatomy.³ Secondly, surgeons must be prepared for potential difficulties with stent removal and the high likelihood of requiring PA reconstruction, tailoring their operative plan accordingly. Thirdly, the choice of stent type and potentially minimizing the duration of implantation (where feasible based on patient growth and clinical status) might influence the surgical interface, although more data are needed to confirm this. Finally, close postoperative surveillance of PA patency is warranted, given the risk of residual or recurrent stenosis requiring further intervention.²

4.2. Future Research

Looking forward, several avenues require further investigation. Prospective, multicenter studies comparing specific surgical techniques for stent management and PA reconstruction after PDA stenting are needed to identify optimal strategies. Long-term follow-up extending beyond the immediate postoperative period is crucial to understand the durability of PA reconstructions, the incidence of late complications, functional outcomes (e.g., exercise capacity), and overall survival compared to patients palliated with surgical shunts. The role of advanced imaging modalities, such as cardiac CT or MRI, in pre-operative surgical planning to better delineate stent position, vessel wall integration, PA anatomy, and potential airway interactions¹³ deserves further exploration. Perhaps most significantly, the development and clinical application of bioresorbable stents hold considerable

promise.¹⁴ A stent that effectively palliates the patient but resorbs before the subsequent surgery could potentially eliminate the challenges associated with stent removal and minimize stent-induced PA injury, fundamentally altering the surgical landscape after ductal stenting. Clinical data on the performance and long-term effects of such devices are eagerly awaited.

4.3. Limitations

This review has several limitations. The findings are based predominantly on retrospective observational studies ², often from single institutions ³, which are susceptible to selection bias and confounding. Heterogeneity in patient populations, stent types, surgical techniques, and outcome reporting across studies limited the potential for quantitative synthesis (meta-analysis) for many outcomes. Publication bias may also be present. Furthermore, as noted in the methods, the inability to access the specific contents of the target PICS collection ³⁰ means that the novelty of this review relative to potential existing papers within that collection could not be definitively confirmed. Finally, detailed long-term outcome data remain sparse in the current literature.

5. Conclusions

Surgical intervention following initial palliation with PDA stenting is a necessary step for most patients with duct-dependent pulmonary circulation and is generally feasible with acceptable risk. However, this review highlights that the procedure presents unique surgical challenges, particularly concerning the management of the indwelling stent and the frequent requirement for pulmonary artery reconstruction. While techniques have evolved, potentially mitigating earlier difficulties with stent removal, the impact on PA integrity remains a significant consideration, often necessitating complex surgical repair. The data underscore a shift in surgical complexity from the initial palliation (shunt surgery) to the subsequent repair phase (stent removal/PA reconstruction). Further research focusing on optimizing surgical techniques, understanding long-term PA outcomes, and evaluating novel technologies like bioresorbable stents is essential to refine the management pathway for these complex patients. Careful pre-procedural planning and tailored surgical approaches remain paramount when operating after PDA stenting.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Healthy Steps Pediatrics (protocol code 07-2025-141 and July 1, 2025).

Informed Consent Statement: Patient consent was waived due to all data being retrospective for this study.

Data Availability Statement: Data available at reasonable request to author.

Conflicts of Interest: The authors declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism

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