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Pediatric Coronary Artery Bypass Grafting: Surgical Innovations, Challenges, and Future Directions

Gandikota Renu[1*], Siri Goud Cheruku[2], Deepna Reddy Patlolla[3*] and Parth Sandeep Lele[4]

[1]Government Medical College, Suryapet, Telangana, India
[2]Kamineni Academy of Medical Sciences and Research Centre, Hyderabad, Telangana, India
[3]Kakatiya Medical College, Warangal, Telangana, India
[4]Terna Medical College, Mumbai, Maharashtra, India

Abstract

Pediatric coronary artery bypass grafting (CABG) is a rare but life-saving intervention for children with complex coronary pathologies, including congenital anomalies, Kawasaki disease, and iatrogenic injuries. Unlike adult CABG, pediatric cases present unique challenges due to small vessel anatomy, growth considerations, and diverse etiologies, necessitating specialized surgical and perioperative strategies. This review addresses the critical need for synthesizing current evidence to guide clinicians in optimizing outcomes for these vulnerable patients. The review highlights key insights, including the superiority of the internal thoracic artery (ITA) as a conduit for its long-term patency and growth adaptability, while acknowledging limitations of alternative grafts. It explores evolving techniques such as off-pump CABG, hybrid revascularization, and microsurgical advancements tailored to pediatric anatomy. Perioperative management, including anesthetic considerations and antiplatelet therapy, is emphasized as pivotal for reducing complications. Clinical studies demonstrate promising short- and mid-term outcomes, though graft durability and reintervention risks warrant further investigation. The review also underscores the importance of multidisciplinary collaboration and centralized care in low-volume, high-complexity cases. Finally, it identifies gaps in standardized protocols and the need for robust long-term follow-up data. Future research should prioritize multicenter studies to establish evidence-based guidelines and refine surgical techniques for pediatric CABG. Innovations in conduit technology, imaging, and personalized pharmacologic regimens hold promises for improving graft longevity and patient survival. By addressing these gaps, the field can advance toward safer, more effective revascularization strategies that ensure children with coronary pathologies achieve optimal long-term outcomes.

Keywords: Congenital coronary anomalies, Graft patency, Kawasaki disease, Pediatric cardiac surgery, Revascularization, Surgical techniques, Thoracic artery grafts

Correspondence to: Gandikota Renu and Deepna Reddy Patlolla, Government Medical College, Suryapet, Telangana, India and Kakatiya Medical College, Warangal, Telangana, India.

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Introduction

CABG is a well-established surgical intervention for adults with coronary artery disease, but its application in pediatric patients remains rare and uniquely challenging [1-3]. Unlike adults, where atherosclerosis predominates, children requiring CABG typically present with conditions such as congenital coronary anomalies, Kawasaki disease, or iatrogenic injuries from prior cardiac surgeries [4-6]. These cases demand specialized surgical expertise due to the small size of pediatric coronary arteries and the need for grafts that accommodate growth. The evolving landscape of pediatric CABG emphasizes tailored techniques, including conduit selection and innovative grafting strategies, to optimize long-term outcomes [7-9].

The indications for pediatric CABG are distinct and often complex. Kawasaki disease, for instance, can lead to coronary aneurysms and stenosis, while congenital anomalies like anomalous aortic origin of a coronary artery may necessitate urgent revascularization [10-12]. Additionally, iatrogenic injuries during other cardiac procedures or genetic disorders such as familial hypercholesterolemia can precipitate the need for bypass surgery in children [13]. These diverse etologies underscore the importance of a nuanced approach to diagnosis and surgical planning. Surgical techniques in pediatric CABG prioritize durability and growth potential. The ITA is the conduit of choice due to its superior patency rates and adaptability to a child's developing anatomy [14-16]. However, challenges such as vessel size and spasm risk limit the use of alternative conduits like the radial artery. Advances in microsurgical methods and anastomotic techniques have further refined the precision required for these procedures, though technical hurdles persist.

The debate between on-pump and off-pump CABG continues in pediatric care, with limited data to guide standardized practices [17-19]. While off-pump techniques may reduce complications like stroke, their feasibility in children depends on anatomical constraints and surgical experience. Minimally invasive and robotic-assisted approaches, though promising, remain underutilized in pediatrics due to technical and logistical barriers. Hybrid revascularization, combining CABG with percutaneous interventions, offers a potential middle ground for select cases [20, 21]. Anesthetic and postoperative management are critical to the success of pediatric CABG [22]. Hemodynamic stability, myocardial protection, and vigilant monitoring for complications like graft thrombosis or infection are paramount [23, 24]. Postoperatively, antiplatelet therapy and long-term surveillance ensure graft patency and detect late-term issues, highlighting the need for multidisciplinary collaboration.

Despite its rarity, pediatric CABG is a lifeline for children with otherwise untreatable coronary pathologies [25]. Ongoing research and clinical innovation aim to address the unique challenges of this population, from refining surgical techniques to improving perioperative care. As the field advances, the goal remains clear: to deliver safe, effective, and durable revascularization for pediatric patients, enabling them to thrive into adulthood.

This review explores the intricacies of pediatric CABG, from indications and surgical strategies to perioperative considerations, offering insights into the clinical studies for this specialized procedure. By synthesizing current evidence and clinical experiences, the review aims to provide a comprehensive resource for clinicians navigating the complexities of coronary revascularization in children.

Indications for Pediatric CABG

The primary indications for CABG in children differ significantly from those in adults. While atherosclerosis is the leading cause of coronary artery disease requiring CABG in adults [26, 27], in children (Table 1), the most common indications include:

- Kawasaki disease: This inflammatory condition can lead to coronary artery aneurysms and subsequent stenosis, necessitating bypass grafting [4].
- Congenital heart disease: CABG may be required as part of the surgical correction of congenital heart defects, such as the anomalous origin of the left coronary artery from the pulmonary artery or transposition of the great arteries [4, 28].
- Iatrogenic injury: Coronary artery damage can occur during complex cardiac surgeries, requiring immediate bypass grafting [4].
- Familial hypercholesterolemia: Homozygous familial hypercholesterolemia, a rare genetic disorder, can cause severe premature coronary artery disease even in childhood, potentially requiring CABG [4].
- Anomalous aortic origin of coronary artery: Surgical management may involve CABG with either arterial or venous graft conduits with or without ligation of the proximal right coronary artery [29]. Anomalous aortic origin of the left coronary artery with intraseptal course is a rare coronary anomaly associated with an increased risk of myocardial ischemia. Surgical techniques included CABG [28].

Unique Challenges in Pediatric CABG

Pediatric CABG presents distinct challenges that differentiate it from adult CABG, requiring specialized expertise and adaptive strategies (Table 2). The most prominent hurdle is the small caliber of pediatric coronary arteries, which demand microsurgical precision for anastomosis and increases the risk of technical complications such as graft kinking or stenosis [30-32]. Unlike adult vessels, children's coronary arteries are more prone to vasospasm, particularly when using arterial conduits, necessitating careful pharmacologic management during and after surgery [33-35]. Growth considerations further complicate pediatric revascularization. Conventional grafts must

Table 1: Indications and etiologies for pediatric CABG.

Category	Specific condition	Pathophysiology	Clinical presentation	Surgical considerations
Congenital anomalies	Anomalous aortic origin of coronary artery	Abnormal coronary ostium location/angulation	Myocardial ischemia, sudden cardiac death	Coronary reimplantation vs CABG with ITA
	Anomalous left coronary artery from pulmonary artery	Coronary steal phenomenon	Heart failure, mitral regurgitation	Direct reimplantation preferred; CABG if not feasible
Acquired conditions	Kawasaki disease	Coronary arteritis → aneurysms/ stenosis	Myocardial infarction, angina	ITA grafting; may require aneurysm resection
	Iatrogenic coronary injury	Surgical trauma during cardiac procedures	Acute ischemia post-op	Emergency CABG; microsurgical techniques
Genetic/metabolic	Homozygous familial hypercholesterolemia	Premature atherosclerosis	Accelerated CAD in childhood	Total arterial grafts; aggressive medical therapy
Other	Post-transplant coronary vasculopathy	Chronic rejection → diffuse stenosis	Progressive heart failure	CABG often palliative; limited graft options

Table 2: Unique challenges in pediatric CABG.

Challenge category	Specific issue	Impact on surgery	Mitigation strategies	Clinical consequences
Anatomic factors	Small vessel caliber (1 - 2 mm)	Technical difficulty in anastomosis; higher risk of graft stenosis/thrombosis	Microsurgical techniques; magnified visualization; ITA preferential use	Increased perioperative graft failure risk
	Coronary vasospasm	Intraoperative ischemia; reduced graft flow	Topical vasodilators (papaverine); calcium channel blockers	Hemodynamic instability
Growth considerations	Somatic growth mismatch	Fixed-diameter grafts may become inadequate over time	Growth-adapted conduits (ITA); staged revision planning	Late graft failure; need for reintervention
Pathologic complexity	Diffuse disease (e.g., Kawasaki)	Limited distal targets; abnormal vessel walls	Sequential grafting; hybrid approaches (CABG + percutaneous coronary intervention)	Suboptimal revascularization
	Aneurysmal segments	Thrombus risk; compromised anastomotic sites	Aneurysmorrhaphy/conduit tailoring; antiplatelet therapy	Thromboembolic events
Physiologic vulnerabilities	Immature myocardium	Increased reperfusion injury susceptibility	Modified cardioplegia (blood-based); controlled reperfusion	Postoperative ventricular dysfunction
Operational factors	Low case volumes	Limited surgeon experience; lack of standardized protocols	Centralized care at high-volume centers; simulation training	Variable outcomes across institutions
	Lack of pediatric-specific devices	Adult equipment unsuitable for small anatomy	Customized instruments; off-label use of microvascular tools	Prolonged operative times

accommodate somatic growth over decades, raising concerns about long-term patency and the potential need for reintervention. This is particularly critical in infants and young children, whose coronary anatomy may evolve with age. The choice of conduit-prioritizing growth-adapted options like the ITA-becomes a pivotal decision with lifelong implications [36, 37].

Additionally, etiologies requiring pediatric CABG (e.g., Kawasaki disease, congenital anomalies) often involve diffuse or complex coronary pathology rather than focal lesions [38-40]. Surgeons frequently encounter abnormal vessel walls (e.g., aneurysmal segments in Kawasaki disease) or atypical anatomy (e.g., intramural coronary courses), which may require innovative bypass techniques or hybrid approaches [41-43]. These conditions also predispose patients to accelerate graft atherosclerosis, even in childhood, mandating aggressive long-term surveillance. The physiologic resilience of pediatric myocardium contrasts with its vulnerability to ischemic injury during surgery. While children often tolerate longer cross-clamp times than adults, their immature myocardium is more susceptible to reperfusion injury and edema [44, 45]. This paradox necessitates refined myocardial protection strategies, including tailored cardioplegia solutions and meticulous temperature management during cardiopulmonary bypass.

Finally, the rarity of pediatric CABG limits institutional experience and evidence-based standardization [46, 47]. Most centers perform fewer than five cases annually, complicating the development of surgical proficiency and consistent postoperative protocols. This underscores the importance of centralized care in high-volume pediatric cardiac centers and collaborative research to establish best practices. These unique challenges highlight the need for a multidisciplinary, patient-tailored approach that integrates microsurgical innovation, growth-accommodating strategies, and lifelong surveillance-themes that will be explored in the subsequent surgical techniques section.

Surgical Techniques

The surgical techniques and materials used in pediatric CABG are distinct from those in adults due to the unique physiological considerations in children, such as growth potential and long-term patency of grafts [48-50]. This section explores the surgical techniques associated with pediatric CABG, highlighting the use of ITAs and microsurgical techniques.

Conduit selection

The choice of conduit is crucial for the long-term success of CABG. In pediatric patients, the ITA, also known as the internal mammary artery, is generally the preferred conduit due to its superior long-term patency and growth potential compared to saphenous vein grafts [1, 4, 27]. Komarov et al. [4] found that the use of ITAs in children with Kawasaki disease resulted in significantly better long-term functionality compared to autovenous conduits (87% vs 44%). While radial artery is another arterial option in adults, its use in children is less common due to size limitations and potential for spasm [27, 51].

Grafting strategies

- Single vs multiple grafts: The number of grafts required depends on the extent and location of coronary artery disease. In cases of multivessel disease, multiple arterial grafts are preferred, utilizing both ITAs and potentially the radial artery if size permits [27].

- On-pump vs off-pump CABG: While off-pump CABG is gaining popularity in adults for its potential to reduce the risk of stroke and other complications [52, 53], its use in pediatric CABG is less well-defined. The decision to perform on-pump CABG or off-pump CABG depends on the surgeon's experience and the specific anatomical considerations of the patient [52]. Studies have demonstrated that on-pump CABG demonstrated a significant long-term benefit in patients aged <80 years [54].

- Minimally invasive techniques: Minimally invasive CABG and robotically assisted totally endoscopic CABG are evolving techniques aimed at reducing surgical trauma and improving recovery times [55-57]. However, their application in pediatric CABG is limited due to the technical challenges associated with small vessels and the need for specialized equipment [55].

- Hybrid revascularization: Hybrid coronary revascularization, which combines CABG with percutaneous coronary intervention, is another evolving strategy [46, 58]. Hybrid coronary revascularization may be considered in select cases where complete surgical revascularization is not feasible or desirable.

Specific surgical approaches

- Anomalous coronary arteries: In cases of anomalous coronary arteries, surgical techniques vary depending on the anatomy and course of the anomalous artery [29]. Options include unroofing the intramural segment, reimplantation of the native artery, or CABG [28, 29].

- Diffuse coronary disease: Fukui and Takanashi [59] describe techniques for bypassing diffusely diseased coronary arteries, including long segmental reconstruction with or without endarterectomy. This approach can be particularly useful in cases of Kawasaki disease where coronary arteries are diffusely affected.

- Distal anastomosis techniques: Palanisamy et al. [60] introduced a novel 'double cobra head' technique of distal coronary anastomosis, which may be useful in situations with limited conduit availability or target vessels with bifurcation lesions.

While pediatric CABG has shown promising results, it remains a technically challenging procedure due to the small size of coronary arteries in children and the need for precise surgical techniques. The choice of graft material, particularly the use of ITAs, plays a critical role in the success of these surgeries. Despite the challenges, advancements in surgical techniques and materials continue to improve outcomes for pediatric patients requiring coronary revascularization.

Clinical Studies

Pediatric CABG is a rare procedure, and the landscape of randomized clinical trials in pediatric cardiac surgery is limited, with most studies focusing on other aspects of cardiac surgery rather than CABG specifically. The available literature highlights the challenges and current research directions in pediatric cardiac surgery, including myocardial protection strategies, ischemic preconditioning, and antithrombotic use. These studies provide insights into the methodologies and outcomes of pediatric cardiac surgery trials, which can indirectly inform the context of pediatric CABG.

A single-center (Children's Hospital of Fudan University, Shanghai, China) cohort study [61] investigated the outcomes of total arterial CABG in pediatric patients with Kawasaki disease related coronary artery anomalies. The study included 46 patients who underwent CABG between January 2015 and January 2024. The study involved 46 pediatric patients with a median age at surgery of 9 years (range, 4.8 to 16.8 years) and a median weight of 30.8 kg (range, 17.0 to 67.2 kg). A total of 72 arterial grafts were used across all patients, comprising 44 ITAs and 28 radial arteries. 16 patients (34.8%) received off-pump CABG. This group had a significantly older median age ($p < 0.05$) and shorter median operation duration ($p = 0.019$) compared to the on-pump CABG group. Outcomes regarding perioperative morbidity and postoperative recovery were comparable between off-pump CABG and on-pump CABG groups. All patients survived during a median follow-up period of 31.5 months (range, 7 to 108 months). Major adverse cardiac events occurred in only one patient, who was found to have a 90% stenosis in the distal anastomosis of a right ITA to right coronary artery graft two years post-CABG, requiring percutaneous coronary intervention. The incidence of freedom from major adverse cardiac events was 100% at 1 year, and 96.7% at both 3- and 5-years post-CABG. No nonfatal myocardial infarction, angina pectoris, or ventricular tachyarrhythmias were recorded in any other patients. All grafts remained patent during follow-up, except for the single case with distal anastomosis stenosis. Functional occlusion occurred in 3 patients due to competitive blood flow. Specifically, 2 were radial arteries related (1 radial artery to right coronary artery, 1 left ITA -radial arteries composite to right coronary artery) and 1 was left ITA to left anterior descending. The median left ventricular ejection fraction at the last follow-up was 0.68 (range, 0.48 to 0.78). Among 18 patients with preoperative myocardial infarction evidence, 5 had a left ventricular ejection fraction < 0.5 before CABG, and only one remained below 0.5 (0.48) after 5 years. Cardiac magnetic resonance imaging and myocardial perfusion imaging showed that myocardial ischemia could recover to varying degrees 1 to 2 years after revascularization. All patients had coronary aneurysms before CABG, with giant aneurysms (diameter >8 mm) found in 32 patients and medium-sized in 14. Coronary artery aneurysmectomy or plasty with thrombectomy was performed in 8 patients. Postoperative catheterization showed recanalization in 8 patients. In summary, the study demonstrates that total arterial CABG is a safe and effective surgical option for pediatric patients with Kawasaki disease-related coronary artery anomalies, showing excellent short-term outcomes with high graft patency and good cardiac function. Off-pump CABG appears to be a viable option for selected cases, with comparable outcomes to on-pump procedures.

A study by Dionne et al. [62] compared outcomes of CABG and percutaneous coronary intervention in patients who developed coronary artery aneurysms following Kawasaki disease. The study included 22 cases from 5 centers in Canada. Of these, 11 patients underwent CABG, 10 underwent percutaneous coronary intervention, and 1 underwent systemic thrombolysis. The average age at intervention was similar between the CABG and percutaneous coronary intervention groups (8.3 ± 3.9 years for CABG vs 11.3 ± 4.9 years for percutaneous coronary intervention, $p = 0.14$). The time elapsed from Kawasaki disease diagnosis to intervention was also comparable between the groups (5.6 ± 4.1 years for CABG vs 6.5 ± 4.7 years for percutaneous coronary intervention, $p = 0.64$). Interventions were primarily based on angiography in 15 patients or a cardiac event in 7 patients, with no significant difference in this basis between the CABG and percutaneous coronary intervention groups ($p = 0.24$). Patients undergoing CABG were significantly more likely to receive multivessel intervention compared to those undergoing percutaneous coronary intervention (73% vs 10%, $p = 0.006$). No patients required reintervention after CABG. In contrast, 6 patients required reintervention after percutaneous coronary intervention, and 1 after systemic thrombolysis, indicating a statistically significant difference ($p = 0.004$). Before intervention, signs of ischemia (on stress testing or methoxyisobutylisonitrile) were present in 15 patients. Following the last intervention, ischemia persisted in 9 patients. A significantly higher proportion of patients in the CABG group (80%) continued to show signs of ischemia compared to the percutaneous coronary intervention group (17%) ($p = 0.01$). In summary, this Canadian series suggests that CABG, often involving multivessel intervention, demonstrated superiority over percutaneous coronary intervention in terms of reintervention rates. However, the persistence of ischemia was higher in the CABG group. The authors note that larger studies are needed to better define patient selection criteria for percutaneous coronary intervention in this population.

A study by Vida et al. [63], a European multicenter effort, evaluated the hospital and midterm results of different surgical revascularization techniques in pediatric patients. The findings highlight the effectiveness of these procedures while identifying factors associated with mortality and complications. The study included 80 pediatric patients from 13 European Congenital Heart Surgeons Association centers, with a median age at the time of coronary procedure of 2.3 years (ranging from 2 days to 16.9 years). Notably, 41.2% of patients were younger than 12 months. A significant portion, 42.5% (34 patients), required an emergency procedure. Sixty-five patients underwent pediatric CABG, while 27 underwent other coronary artery procedures. Twelve patients had a combination of both. Pediatric CABG was performed in 60 patients as a single procedure and in 5 patients as a double procedure. Other coronary artery procedures were performed in 15 isolated cases and were associated with pediatric CABG in 12 cases. Emergency PCABG was performed in 29 patients, either as an unplanned intraoperative rescue during corrective operations (21 patients) or due to clinical status and symptoms after initial surgery (8 patients). The remaining 36 patients underwent planned pediatric CABG procedures. Twelve patients (15%) died in the hospital. Hospital mortality was significantly related to younger age at surgery ($p = 0.02$) and the need for an emergency procedure ($p = 0.0004$). At logistic regression analysis, emergent surgery was found to be associated with increased hospital mortality (odds ratio, 21.5; 95% confidence interval (CI), 2.6 to 177.1). Patients who died required longer cardiopulmonary bypass and cross-clamp times and more frequently needed postoperative extracorporeal membrane oxygenation support. The main causes of death were left ventricular infarction ($n = 9$), right ventricular infarction ($n = 1$), cardiac arrest ($n = 1$), and extracorporeal membrane oxygenation-related complications ($n = 1$). Forty-five postoperative complications were reported in 38 patients (47%), including difficulty weaning from cardiopulmonary bypass. The median follow-up time was 7.6 years, with a range of 0.9 to 23 years. There were 3 late cardiac deaths, all occurring after a median time of 4 years (range, 9 months to 8.8 years) after pediatric CABG. Four patients (5.8%) died during follow-up, with 3 cardiac deaths attributed to left ventricular failure ($n = 2$) and sudden infarction ($n = 1$). Fourteen patients (20.5%) presented with symptoms, including congestive heart failure ($n = 10$) and angina ($n = 4$). These symptoms were significantly associated with a low ejection fraction ($p < 0.001$) and the presence of moderate or severe mitral valve regurgitation ($p = 0.0003$). Symptoms at follow-up were found to be associated with the grade of mitral regurgitation at discharge and at follow-up, and with the left ventricular ejection fraction at follow-up. Six patients underwent a reintervention for impaired myocardial perfusion. All of them had a stenotic or atretic pediatric CABG ($p = 0.001$), and the majority were symptomatic (5 of 6 patients; 83.3%; $p = 0.001$). Reoperations or reinterventions were performed in 6 of 68 survivors (8.8%), with these patients having a lower left ventricular ejection fraction at follow-up and moderate or severe mitral regurgitation and being symptomatic.

All 6 patients exhibited stenosis of the previously positioned pediatric CABG at control coronary angiography (Figure 1). 45 of 64 survivors (70%) underwent a control coronary angiography. Pediatric CABGs were patent in 27 patients, stenotic in 5, and occluded in 10. Other coronary artery procedures were patent in 3 patients and stenotic in 1. No association was found between antithrombotic therapy and patency of pediatric CABG or other coronary artery procedures at follow-up. In conclusion, both pediatric CABG and other coronary artery procedures are suitable surgical options for pediatric patients with impaired myocardial perfusion, leading to increased operative and midterm survival. However, careful long-term follow-up is essential to prevent and treat potential causes of further myocardial ischemia. The study also highlights the importance of prompt and rescue revascularization in improving outcomes, even though graft patency may not always be necessary for sufficient cardiac blood flow.

A study by Hohri et al. [64] investigated the outcomes of CABG for congenital coronary artery anomalies in infants and young children, reporting favorable short- and mid-term results. The study observed no 30-day or in-hospital mortality among the patients. Furthermore, no cardiac events, such as perioperative myocardial infarction, were reported after discharge (Figure 2). Postoperatively, patients did not experience any ischemic symptoms. All grafts were patent during postoperative examinations before discharge, indicating a 100% initial graft patency rate. At the follow-up period, the overall graft patency rate was 80.0% (4 out of 5 grafts). One graft was found to be occluded at 2.5 years postoperatively due to flow competition. There was no significant improvement in postoperative left ventricular ejection fraction values compared to preoperative values. The median preoperative left ventricular ejection fraction was 77.6% (range: 67.0 to 88.0%), and the median postoperative left ventricular ejection fraction was 76.4% (range: 66.0 to 85.0%). Despite this, the good left ventricular function (left ventricular ejection fraction >60%) contributed to a positive postoperative outcome. During the entire follow-up period, which had a median duration of 4.2 years (range: 2.3 to 6.8 years), no deaths or cardiac events occurred. While the short- and mid-term outcomes and patency rates were satisfactory, the authors emphasize the need for careful and continuous follow-up due to the unknown long-term outcomes. In summary, CABG appears to be a useful and effective strategy for coronary revascularization in infants and young children with congenital coronary artery anomalies, demonstrating satisfactory short- and mid-term patency rates and surgical outcomes with no observed mortalities or major cardiac events in the study cohort. However, the limited duration of follow-up necessitates ongoing monitoring to assess long-term efficacy.

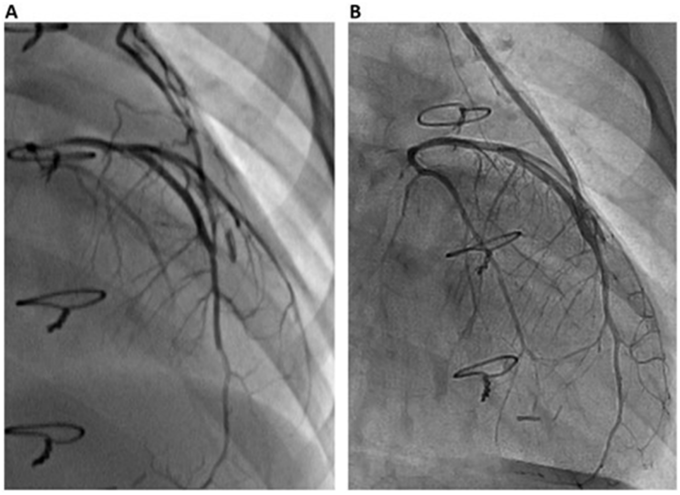

Figure 2: Longitudinal angiographic assessment of graft function. **(A)** Early postoperative coronary angiography documented successful graft perfusion. **(B)** Subsequent evaluation at 17 months postoperatively demonstrated continued patency of the left ITA graft, confirming sustained surgical revascularization efficacy [64].

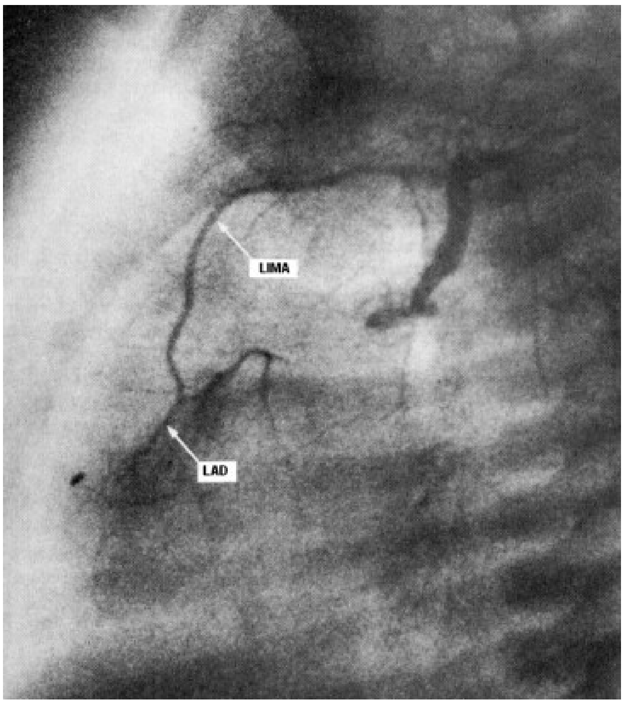

Figure 1: Post-revascularization angiography documenting optimal patency of a left internal mammary artery graft anastomosed to the left anterior descending artery in a critically ill neonate presenting with dextro-transposition of the great arteries, ventricular septal defect, and an intramural course of the anomalous left coronary artery [63].

The EXCEL trial by Stone et al. [65] investigated the long-term outcomes of percutaneous coronary intervention with drug-eluting stents compared to CABG in patients with left main coronary artery disease of low or intermediate anatomical complexity. At 5 years, there was no significant difference between the percutaneous coronary intervention and CABG groups regarding the primary composite outcome of death, stroke, or myocardial infarction. Specifically, 22.0% of patients in the percutaneous coronary intervention group experienced a primary outcome event, compared to 19.2% in the CABG group, resulting in a difference of 2.8% points (95% CI, -0.9 to 6.5; p = 0.13). Death from any cause occurred more frequently in the percutaneous coronary intervention group (13.0%) than in the CABG group (9.9%), showing a difference of 3.1% points (95% CI, 0.2 to 6.1). The excess deaths in the percutaneous coronary intervention group were primarily due to noncardiovascular causes, such as cancer and infection, particularly in late follow-up. The incidences of definite cardiovascular death were similar between the percutaneous coronary intervention (5.0%) and CABG (4.5%) groups, with a difference of 0.5% points (95% CI, -1.4 to 2.5). The incidences of myocardial infarction were not significantly different between the percutaneous coronary intervention (10.6%) and CABG (9.1%) groups, with a difference of 1.4% points (95% CI, -1.3 to 4.2). However, periprocedural myocardial infarction was less frequent with percutaneous coronary intervention, while non-periprocedural myocardial infarction was more frequent with percutaneous coronary intervention. All cerebrovascular events were less frequent after percutaneous coronary intervention (3.3%) than after CABG (5.2%), a difference of -1.9% points (95% CI, -3.8 to 0). This difference was mainly driven by transient ischemic attacks, which were less frequent after percutaneous coronary intervention. The incidence of stroke alone was not significantly different between the two groups (percutaneous coronary intervention 2.9% vs CABG 3.7%). Ischemia-driven revascularization was more frequent after percutaneous coronary intervention (16.9%) than after CABG (10.0%), with a difference of 6.9% points (95% CI, 3.7 to 10.0). Most revascularization events after percutaneous coronary intervention were repeat percutaneous coronary intervention procedures. Therapy failure (defined as definite stent thrombosis or symptomatic graft stenosis or occlusion) was less frequent after percutaneous coronary intervention (1.1%) than after CABG (6.5%), with a difference of -5.4% points (95% CI, -7.2 to -3.6). For patients with left main coronary artery disease of low or intermediate anatomical complexity, the study concluded that there was no significant difference between percutaneous coronary intervention and CABG concerning the composite outcome of death, stroke, or myocardial infarction at 5 years. While percutaneous coronary intervention showed an early benefit in terms of fewer periprocedural adverse events, this advantage was attenuated over time due to a higher incidence of later events, particularly death from any cause and repeat revascularization, leading to similar cumulative outcomes at 5 years.

While the current randomized controlled trials provide valuable insights into specific interventions and techniques, the direct application to pediatric CABG remains limited due to the scarcity of trials specifically addressing this procedure. The challenges in conducting randomized controlled trials in this field include ethical considerations, small patient populations, and the complexity of congenital heart diseases. Future research should focus on multicenter collaborations to conduct high-quality randomized controlled trials that can provide robust evidence for pediatric CABG practices. Additionally, developing standardized outcome measures and improving trial design could enhance the quality and applicability of research findings in this area.

Anesthetic Management

Anesthetic management in pediatric CABG requires meticulous planning and expertise to address the unique physiological and anatomical challenges of children [66]. Unlike adults, pediatric patients often present with congenital or acquired coronary pathologies that demand tailored anesthetic strategies to ensure hemodynamic stability and myocardial protection [67]. Key considerations include preoperative optimization, intraoperative monitoring, and pharmacologic management to mitigate risks such as ischemia, arrhythmias, and systemic inflammation. The anesthesiologist plays a pivotal role in coordinating with the surgical team to balance perfusion demands and minimize myocardial oxygen consumption during the procedure [68, 69].

Preoperative assessment is critical to identify risk factors and tailor the anesthetic plan. Children with Kawasaki disease or congenital coronary anomalies may exhibit compromised ventricular function or collateral-dependent circulation, necessitating careful evaluation of cardiac reserve [70]. Baseline echocardiography and coronary imaging help guide intraoperative decisions, while laboratory tests assess coagulation status and end-organ function [71]. Premedication with anxiolytics may be warranted to reduce stress-induced catecholamine surges, particularly in older children, though caution is required in infants with hemodynamic instability.

Induction and maintenance of anesthesia must prioritize hemodynamic stability. A balanced technique combining opioids, inhalational agents, and muscle relaxants is commonly employed to avoid excessive myocardial depression or tachycardia [72, 73]. High-dose opioid regimens, such as fentanyl or sufentanil, provide stable hemodynamics and blunt stress responses, while volatile anesthetics like sevoflurane offer cardioprotective effects [74]. Invasive monitoring, including arterial and central venous lines, is essential for real-time assessment of blood pressure, filling pressures, and cardiac output [75]. Transesophageal echocardiography provides invaluable feedback on ventricular function and graft patency.

Myocardial protection strategies are tailored to the surgical approach. For on-pump CABG, meticulous management of cardiopulmonary bypass is crucial, including optimal anticoagulation, temperature regulation, and perfusion pressures [76]. Pediatric patients are particularly vulnerable to cardiopulmonary bypass-induced systemic inflammation and capillary leak syndrome, necessitating judicious fluid management and anti-inflammatory interventions [77]. Off-pump CABG, though less common in children, demands precise anesthetic titration to maintain stable hemodynamics during cardiac manipulation [78]. Techniques such as Trendelenburg positioning or pharmacologic support with vasopressors may be required to optimize coronary perfusion.

Pharmacologic adjuncts play a key role in reducing perioperative morbidity. Beta-blockers and calcium channel blockers may be used to prevent coronary spasm, especially in patients with Kawasaki disease or arterial grafts [79]. Antifibrinolytic agents like tranexamic acid minimize bleeding, while antiplatelet therapy (e.g., aspirin) is often initiated postoperatively to maintain graft patency [80]. Glycemic control and electrolyte balance are closely monitored to prevent arrhythmias and metabolic derangements [81]. The anesthesiologist must also be prepared to manage emergent scenarios, such as acute graft failure or ventricular fibrillation, with prompt intervention.

Emergence and postoperative transitions require careful planning to avoid hemodynamic perturbations. Extubation in the operating room may be feasible for stable patients, though many children benefit from continued mechanical ventilation to ensure adequate oxygenation and reduce myocardial workload [82]. Pain management, utilizing multimodal analgesia with regional techniques or patient-controlled systems, enhances recovery and reduces opioid-related side effects [83]. Close monitoring in the cardiac intensive care unit is essential to detect early complications, such as bleeding, tamponade, or low cardiac output syndrome, which require immediate intervention.

Long-term collaboration between anesthesiologists, surgeons, and intensivists is vital for optimizing outcomes in pediatric CABG [84]. Advances in monitoring technologies, such as near-infrared spectroscopy for cerebral and somatic oxygenation and evolving pharmacologic strategies continue to refine perioperative care. Future research should focus on standardizing anesthetic protocols for rare pediatric coronary conditions and evaluating the impact of novel agents on graft longevity and neurodevelopmental outcomes. By integrating evidence-based practices with individualized care, the anesthetic team can significantly contribute to the success of these complex surgeries.

Postoperative Management

The postoperative management of pediatric patients following CABG requires a multidisciplinary approach to address the unique challenges of this population. Unlike adults, children undergoing

CABG often have complex congenital or acquired coronary pathologies that necessitate vigilant monitoring and tailored interventions [85]. The immediate postoperative period is critical for detecting complications such as graft failure, arrhythmias, or low cardiac output syndrome. Close hemodynamic monitoring, including continuous arterial blood pressure, central venous pressure, and cardiac output measurements, forms the foundation of postoperative care in the cardiac intensive care unit [86].

Early extubation may be considered for stable patients to reduce ventilator-associated complications, though many children require prolonged mechanical ventilation due to hemodynamic instability or pulmonary edema [87]. Ventilator strategies should aim to optimize oxygenation while avoiding excessive positive end-expiratory pressure, which can compromise cardiac filling. Sedation and analgesia must be carefully balanced to minimize stress responses without causing respiratory depression or hemodynamic compromise [88]. Multimodal pain management, incorporating opioids, regional techniques, and adjuncts like acetaminophen, enhances comfort while facilitating early mobilization.

Graft patency and myocardial perfusion are paramount concerns in the postoperative period. Routine electrocardiography and echocardiography help detect signs of ischemia or ventricular dysfunction, while troponin levels provide biochemical evidence of myocardial injury [89]. Antiplatelet therapy, typically low-dose aspirin, is initiated early to prevent graft thrombosis, particularly in arterial conduits [90]. For high-risk patients or those with complex revascularization, dual antiplatelet therapy or anticoagulation may be considered, though bleeding risks must be carefully weighed [91]. In cases of suspected graft failure, urgent imaging with coronary angiography or computed tomography angiography may be required to guide intervention.

Fluid and electrolyte management play a crucial role in maintaining hemodynamic stability. Children are particularly susceptible to capillary leak syndrome following cardiopulmonary bypass, necessitating judicious fluid administration and diuretic therapy to prevent volume overload [92]. Electrolyte imbalances, such as hypokalemia or hypocalcemia, must be promptly corrected to reduce the risk of arrhythmias [93]. Inotropic or vasoactive support with agents like milrinone, epinephrine, or vasopressin may be required for patients with low cardiac output, with dosing tailored to the child's weight and hemodynamic response [94].

Infection prevention and wound care are essential components of postoperative management. Prophylactic antibiotics are administered per protocol, with strict aseptic techniques employed for invasive lines and surgical sites [95]. Pediatric patients, especially those with Kawasaki disease or immunosuppression, are at increased risk for sternal wound infections or sepsis [96]. Early recognition of signs such as fever, leukocytosis, or purulent drainage is critical for timely intervention. Nutritional support, including enteral or parenteral feeding, should be initiated early to promote healing and mitigate the catabolic effects of surgery.

Long-term follow-up is indispensable for monitoring graft patency, cardiac function, and overall growth. Regular outpatient visits with serial echocardiograms, stress testing, and coronary imaging help detect late complications such as graft stenosis or progression of underlying disease. Lifestyle modifications, including dietary counseling and exercise recommendations, are tailored to the child's specific condition, such as familial hypercholesterolemia or residual Kawasaki disease [97]. Psychological support for both the child and family is also integral, as the chronic nature of these conditions can impact quality of life and adherence to medical therapy [98].

Advances in postoperative care continue to improve outcomes for pediatric CABG patients. Emerging technologies, such as wearable hemodynamic monitors and telemedicine platforms, enhance remote monitoring and early detection of complications. Research into biomarkers of graft failure and personalized antiplatelet regimens holds promise for further refining management strategies. By combining rigorous acute care with comprehensive long-term surveillance, clinicians can ensure optimal outcomes for these vulnerable patients, enabling them to transition smoothly into adulthood with preserved cardiac function.

Conclusion

Pediatric CABG represents a critical yet complex intervention for children with rare coronary pathologies, such as Kawasaki disease, congenital anomalies, or iatrogenic injuries. Unlike adult CABG, pediatric cases demand specialized techniques to address small vessel sizes, growth potential, and unique etiologies. The ITA remains the conduit of choice due to its superior patency and adaptability, though challenges like vasospasm and limited alternative conduits persist. Advances in microsurgical methods, hybrid revascularization, and tailored perioperative care have improved outcomes, yet the rarity of these procedures underscores the need for centralized expertise and multidisciplinary collaboration.

Current evidence highlights the efficacy of pediatric CABG in restoring myocardial perfusion, with studies demonstrating high graft patency rates and functional recovery in the short to mid-term. However, long-term data remains scarce, emphasizing the importance of lifelong surveillance to monitor graft durability and cardiac function. The debate between on-pump and off-pump techniques, as well as the role of minimally invasive approaches, continues to evolve, with patient-specific factors guiding surgical decisions. Anesthetic and postoperative management play pivotal roles in mitigating risks such as ischemia, arrhythmias, and infection, while antiplatelet therapy and individualized rehabilitation strategies are essential for sustaining outcomes.

As the field progresses, future research should prioritize multicenter collaborations to standardize practices and address knowledge gaps, particularly in long-term graft performance and quality-of-life metrics. Innovations in conduit technology, imaging, and pharmacologic therapies hold promises for further refining pediatric CABG. Ultimately, the goal is to provide durable revascularization that enables children to thrive into adulthood, underscoring the importance of integrating surgical excellence with holistic, patient-centered care.

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Conflict of Interest

None.

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