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Review

Paradigm Shift in Coronary Bypass Surgery: From Traditional Methods to Future Surgical Strategies

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Abstract

Coronary artery bypass grafting (CABG) remains the gold-standard revascularization strategy for patients with multivessel coronary artery disease, supported by ongoing advancements in surgical techniques, graft selection, and perioperative management. This review primarily focuses on CABG, with occasional comparisons to percutaneous coronary intervention (PCI) when clinically relevant. Traditional CABG techniques have been increasingly challenged by the emergence of minimally invasive, off-pump, and robotic-assisted approaches; however, the optimal strategy for long-term graft patency and improved survival continues to evolve. This review explores the evolution of CABG, with a particular emphasis on comparing arterial and venous grafts in terms of patency and survival outcomes. Meanwhile, while minimally invasive coronary artery bypass grafting and off-pump techniques have shown potential in reducing postoperative complications, their long-term patency rates remain a subject of debate. Robotic-assisted CABG provides enhanced surgical precision and accelerated recovery; however, its widespread adoption remains limited due to high costs and technical complexity. Subsequently, hybrid revascularization strategies, which combine coronary artery bypass grafting and percutaneous coronary intervention, have emerged as promising alternatives for selected patient populations. The future of CABG will likely be shaped by innovations such as bioengineered vascular grafts and artificial intelligence-assisted surgical planning, which have the potential to enhance graft patency, improve surgical precision, and enable more personalized interventions. Nonetheless, individualized surgical planning and optimal graft selection remain critical for achieving long-term success, highlighting the need for further research to establish standardized protocols for incorporating these emerging technologies into routine clinical practice.

Keywords

coronary artery bypass grafting; arterial grafts; robotic-assisted surgery; hybrid revascularization; graft patency

Introduction

Coronary artery disease (CAD) continues to represent a major global health burden, accounting for significant morbidity and mortality across diverse populations. As a cornerstone of cardiac surgery, coronary artery bypass grafting (CABG) is recognized as one of the most effective surgical treatment modalities for patients with significant coronary artery stenosis [1]. Since the first successful CABG procedure was performed in the 1960s, substantial advancements have been made in surgical techniques, graft selection, perioperative care, and long-term clinical outcomes [2].

CABG surgery has been shown to provide superior long-term benefits compared to percutaneous coronary interventions (PCIs), particularly in high-risk patient groups, such as those with multivessel disease, left main coronary artery disease, and diabetes mellitus [3]. Among the various parameters that affect the long-term outcomes of CABG, graft patency is considered the most critical determinant, as it directly influences myocardial perfusion and patient survival over time [2]. One of the main reasons for this advantage is the longer patency of bypass grafts, which ensures more stable myocardial perfusion. Notably, the anastomosis of the left internal mammary artery (LIMA) to the left anterior descending artery (LAD) plays a pivotal role in ensuring long-term graft patency and improving patient outcomes [4]. Additionally, the increasing use of arterial grafts, such as the radial artery and right internal mammary artery, has demonstrated superior long-term patency rates compared to venous grafts, thereby improving patient survival [5].

Several innovative approaches have been introduced in CABG surgery in recent years. Indeed, minimally invasive coronary artery bypass grafting (MICS-CABG) techniques allow surgical revascularization without the need for sternotomy, resulting in a faster recovery and reduced hospital stays [6]. Off-pump coronary artery bypass grafting (OPCAB), a technique performed without cardiopulmonary bypass (CPB), has been associated with a lower incidence of neurological and perioperative complications [7]. Furthermore, robotic-assisted CABG and hybrid revascularization strategies have made surgical interventions less invasive, yielding improved clinical outcomes in selected patient populations [8].

The long-term success of CABG depends on multiple factors, including graft selection, patient comorbidities, and postoperative medical management. Among these, accurate patient selection and meticulous perioperative management are pivotal for minimizing complications and maximizing both graft patency and survival outcomes. Optimal perioperative care, including the use of antiplatelet therapy, statins, and other pharmacological agents, is crucial for preventing postoperative complications and graft occlusion [9]. Moreover, continuous advancements in surgical techniques and optimization of patient selection criteria will play a decisive role in shaping the future direction of CABG. The historical evolution of CABG has witnessed several pivotal transitions, from conventional on-pump techniques to off-pump procedures, and more recently, to minimally invasive and robotic-assisted approaches. Robotic CABG, first introduced in the late 1990s, represented a paradigm shift in surgical revascularization, allowing for enhanced dexterity and precision through small thoracic ports. Subsequently, hybrid revascularization strategies have emerged in response to the increasing complexity of coronary lesions and the need for tailored treatment plans. These strategies combine surgical and percutaneous interventions, integrating the long-term patency advantage of CABG with the flexibility of PCIs. Thus, both robotic CABG and hybrid techniques represent the latest stages in the continuous evolution of coronary surgery toward less invasive, more patient-specific, and technologically integrated solutions [2,6,8,10].

This narrative review aims to provide a comprehensive evaluation of CABG, from its historical evolution to contemporary surgical approaches, graft selection strategies, and long-term outcomes. Special emphasis will be placed on recent advancements, including minimally invasive techniques, the advantages of arterial grafts, and the role of robotic surgery in CABG, based on the latest evidence in the literature.

Literature Review

Overview

This narrative review provides an in-depth synthesis of the current literature on CABG, encompassing its historical evolution, surgical techniques, and clinical outcomes. The selected literature has been analyzed to gain insights into the evolutionary trajectory of CABG, patient outcomes, and potential future developments.

This study does not follow a systematic meta-analysis format and does not aim to test a specific hypothesis. However, similar to systematic review methodologies, the literature selection process was conducted transparently, with clearly defined inclusion and exclusion criteria.

Eligibility Criteria

The literature evaluated in this study was selected based on specific inclusion and exclusion criteria. Articles included in the review primarily consist of studies providing data on CABG surgical techniques, graft selection strategies, and long-term clinical outcomes. Priority was given to studies examining the relationship between CABG and arterial or venous grafts, assessing surgical success rates, and evaluating postoperative patient outcomes. Preference was also given to articles published in journals indexed in the Science Citation Index (SCI) or SCI-Expanded, as well as studies with methodologically robust designs such as randomized controlled trials (RCTs), retrospective analyses, and observational research. Furthermore, studies discussing novel surgical techniques, minimally invasive approaches, robotic-assisted surgery, and the future trajectory of CABG were also considered.

Excluded studies primarily consisted of articles that focused solely on PCIs or those not directly related to CABG. Additionally, case reports, unpublished data, preprints, and studies deemed methodologically insufficient were excluded. Studies that, despite being associated with CABG, failed to assess clinical outcomes sufficiently, lacked technical details, or did not provide survival-related data were also omitted from the review. Throughout this process, priority was given to the most recent literature, incorporating the latest surgical techniques and clinical outcomes, to ensure a comprehensive understanding of the current state and future advancements in CABG. The preference for studies published in English and indexed in the SCI or SCI-Expanded may have introduced a potential selection bias, possibly excluding relevant findings from non-English or non-indexed sources. This limitation was considered during interpretation, and the selected literature was critically evaluated to minimize bias-related distortion.

Information Sources

As part of this study, the literature review was conducted using reputable academic databases, including PubMed, Scopus, Web of Science, and Google Scholar. Priority was given to articles published within the last 20 years; however, seminal studies considered essential for understanding the historical development of CABG were also included. The selection process focused on studies presenting up-to-date scientific data on CABG surgical techniques, graft selection, clinical outcomes, and postoperative complications.

Selection Process

The study selection process was conducted using a three-step approach. In the first stage, a comprehensive search was conducted in the selected databases using relevant keywords, and the titles and abstracts of the retrieved articles were reviewed. In the second stage, full-text articles focusing on technical advancements, graft selection strategies, and clinical success rates in relation to CABG were examined in detail. In the final stage, the methodological quality and relevance of the selected studies were assessed to ensure the inclusion of the most up-to-date and high-quality articles, leading to the final selection of studies for this review. The search strategy was conducted using the following keywords in various combinations: "coronary artery bypass grafting", "CABG", "arterial grafts", "venous grafts", "minimally invasive CABG", "robotic CABG", "hybrid revascularization", "off-pump CABG", and "graft patency". Boolean operators (AND, OR) were utilized to optimize the search results. A total of 412 articles were initially retrieved from PubMed, Scopus, Web of Science, and Google Scholar databases. After removing duplicates and applying inclusion and exclusion criteria, 102 full-text articles were thoroughly reviewed. Of these, 61 studies were selected for final analysis based on their methodological rigor, clinical relevance, and recency.

Data Extraction

The data obtained from these selected studies were categorized according to the fundamental components of CABG, including its historical evolution, surgical techniques, graft selection, clinical outcomes, and future perspectives. From a historical perspective, this review outlines the evolution of CABG from its early applications to modern advancements. In terms of surgical techniques, various approaches such as cardiopulmonary bypass, off-pump CABG, minimally invasive CABG, and robotic-assisted surgery were analyzed.

Regarding graft selection, the patency rates and clinical advantages of the left internal mammary artery, radial artery, and saphenous vein grafts (SVGs) were evaluated. Postoperative outcomes were assessed by examining the long-term effects of CABG on mortality and morbidity, graft patency rates, and potential complications. From a future perspective, the potential role of artificial intelligence (AI), biomaterials, and tissue engineering applications in CABG was explored. All these findings were systematically analyzed and integrated into the review in accordance with its overall framework.

Etiology and Pathophysiology

CAD is a progressive vascular disorder that develops as a result of atherosclerotic processes, leading to myocardial ischemia. CABG is one of the most effective surgical interventions for treating significant coronary artery stenosis. Thus, understanding the fundamental etiological and pathophysiological mechanisms of the disease is crucial for improving surgical success.

A combination of genetic predisposition and environmental factors shapes the etiology of CAD. Moreover, classical risk factors such as hypertension, hyperlipidemia, smoking, diabetes mellitus, and metabolic syndrome accelerate the progression of atherosclerosis, leading to progressive narrowing of the coronary arteries [11]. In particular, the accumulation of low-density lipoprotein (LDL) particles within the vascular wall triggers inflammatory processes, thereby promoting the formation of atherosclerotic plaques. Over time, these plaques may destabilize, rupture, and precipitate thrombotic events, ultimately leading to the development of acute coronary syndrome [12].

Endothelial dysfunction plays a critical role in the pathophysiology of CAD. Normally, the endothelium contributes to vasodilation, antithrombotic activity, and suppression of inflammation. However, as the atherosclerotic process progresses, the endothelial function deteriorates, leading to reduced nitric oxide (NO) production, increased generation of reactive oxygen species (ROS), and elevated levels of inflammatory mediators, ultimately disrupting vascular tone [11]. As endothelial dysfunction worsens, the structural integrity of the vascular wall is compromised, leading to reduced plaque stability. The rupture of these plaques can result in thrombosis, significantly impairing myocardial perfusion and precipitating acute cardiac events [11].

In CAD, ventricular remodeling due to myocardial ischemia is another key pathological process. Chronic ischemia leads to structural changes in myocardial tissue, characterized by fibrosis and the formation of scars. This process contributes to impaired left ventricular function, reduced ejection fraction, and the eventual development of heart failure [13]. Therefore, CABG is designed to reverse the adverse consequences of ischemia by restoring perfusion to viable myocardial tissue that has not yet undergone irreversible fibrotic changes [13].

The type of graft used in CABG can directly influence the pathophysiology of the atherosclerotic process. Arterial grafts, particularly the internal mammary artery (IMA), radial artery, and gastroepiploic artery, offer superior long-term patency rates due to their preserved endothelial integrity and greater vasodilatory capacity. In contrast, SVGs, being of venous origin, are more susceptible to atherosclerotic changes and have a higher risk of long-term occlusion [4]. Studies have demonstrated that using

Table 1. Etiology and pathophysiology of coronary artery disease (CAD).

Factor	Pathophysiological effect	References
Genetic predisposition	Inherited susceptibility increases CAD risk.	[11–13]
Hypertension	Increases vascular resistance and promotes atherosclerosis.	[11]
Hyperlipidemia	LDL accumulation leads to plaque formation.	[11,13]
Smoking	Oxidative stress damages endothelium and increases thrombosis risk.	[14,15]
Diabetes mellitus	Microvascular dysfunction and increased thrombotic risk.	[15,16]
Metabolic syndrome	Combination of risk factors leading to accelerated atherosclerosis.	[11,13]
Endothelial dysfunction	Impaired nitric oxide production and increased vascular inflammation.	[11,13]
Atherosclerotic plaque formation	Progressive narrowing of coronary arteries due to lipid accumulation.	[13]
Thrombosis	Plaque rupture leads to occlusive thrombus formation.	[13]
Myocardial ischemia	Reduced myocardial perfusion leads to ischemic injury and ventricular remodeling.	[13]

CAD, Coronary artery disease; LDL, Low-density lipoprotein.

the IMA significantly reduces postoperative mortality and graft failure rates following CABG [5].

In conclusion, the etiology and pathophysiology of CAD involve a complex interplay of genetic predisposition, environmental risk factors, endothelial dysfunction, atherosclerotic plaque formation, and thrombotic events (Table 1, Ref. [11–16]). CABG remains the most effective surgical intervention for reducing ischemia-related morbidity and mortality; however, surgical success is influenced by patient-specific pathophysiological factors and the type of grafts used. Therefore, personalized surgical planning and optimal graft selection are essential for maximizing the efficacy of CABG.

Risk Factors

Despite being one of the most effective treatment strategies for patients with severe CAD, CABG is associated with multiple risk factors in the preoperative, intraoperative, and postoperative periods. These factors play a crucial role in determining surgical success, graft patency rates, and long-term clinical outcomes, ultimately impacting patient prognosis.

Several major risk factors contribute to the development of CAD and increase the need for CABG, including hypertension, hyperlipidemia, smoking, diabetes mellitus, and metabolic syndrome. Hypertension accelerates atherosclerotic plaque formation by inducing structural changes in the arterial walls, while hyperlipidemia promotes the accumulation of LDL particles within the vascular endothelium, triggering an inflammatory response [14]. Smoking contributes to endothelial dysfunction by increasing oxidative stress and promoting thrombogenic processes, thereby elevating the risk of graft occlusion [15].

Diabetes mellitus is among the most critical prognostic factors in CABG surgery. In diabetic patients, vascular impairment, microvascular dysfunction, increased thrombosis risk, and accumulation of advanced glycation end products in the vessel walls lead to lower graft patency rates and higher postoperative complication rates [15]. Additionally, the risk of graft occlusion is significantly higher, particularly in patients undergoing CABG with saphenous vein grafts. Therefore, the use of the internal mammary artery in this patient group has been shown to provide better long-term outcomes [5].

Age is another significant risk factor in CABG surgery. Furthermore, vascular aging, loss of arterial elasticity, and associated comorbidities contribute to an increased risk of surgical complications in older patients. Likewise, neurological complications, postoperative delirium, renal dysfunction, and pulmonary complications are more frequently observed in older patients after CABG [15]. However, age alone is not considered a contraindication for surgery; rather, overall health status and functional capacity are more decisive factors in the surgical decision-making process.

Sex-based differences also influence CABG outcomes. Female patients generally have smaller coronary artery diameters, which may negatively impact surgical anastomosis success. Indeed, studies have shown that women experience higher postoperative complication rates and longer hospital stays than men, although there is no significant difference in long-term survival [17].

One of the most critical perioperative risk factors is left ventricular dysfunction. Notably, patients with reduced ejection fraction (EF) are at a higher risk of developing low cardiac output syndrome and postoperative heart failure [16]. Therefore, to optimize surgical outcomes, preoperative medical therapy and perioperative cardiovascular support strategies should be carefully implemented and executed.

Inflammatory markers and preoperative biochemical parameters are essential indicators for predicting outcomes after CABG. Elevated C-reactive protein (CRP) levels have been associated with postoperative graft occlusion and systemic inflammatory response syndrome (SIRS). Similarly, increased preoperative urea and creatinine levels are linked to a higher risk of postoperative renal dysfunction, which significantly impacts mortality [3].

Table 2. Major risk factors affecting CABG outcomes.

Risk factor	Impact on CABG	Supporting evidence
Hypertension	Accelerates atherosclerosis, increasing surgical risk.	[14]
Hyperlipidemia	Leads to progressive coronary artery disease.	[14]
Smoking	Endothelial damage and increased risk of graft occlusion.	[15]
Diabetes mellitus	Higher risk of graft failure and postoperative complications.	[5,15]
Age	Older patients have increased surgical risks.	[15]
Gender	Women tend to have smaller arteries, impacting anastomosis.	[17]
Left ventricular dysfunction	Increases risk of postoperative heart failure and complications.	[16]
Inflammatory markers	High CRP levels linked to poor graft outcomes and systemic inflammation.	[3]
Preoperative biochemical parameters	High creatinine and urea levels linked to increased mortality.	[3]
Surgical technique	Off-pump CABG may reduce complications in high-risk patients.	[16]

CABG, coronary artery bypass grafting; CRP, C-reactive protein.

Postoperative risk factors primarily involve mechanisms affecting graft patency and complications. Saphenous vein grafts, in particular, have been reported to exhibit lower long-term patency rates due to early endothelial damage and the progression of atherosclerosis. In contrast, arterial grafts—especially the internal mammary artery—have demonstrated superior long-term patency and more effective maintenance of myocardial perfusion [5].

In conclusion, patient selection and perioperative management play a crucial role in determining the success of CABG. Accurate preoperative risk assessment, optimal graft selection, and appropriate postoperative medical therapy are essential components for improving graft patency and long-term patient survival (Table 2, Ref. [3,5,14–17]).

Diagnosis and Clinical Findings

CAD is diagnosed based on patient symptoms, physical examination findings, and the use of advanced cardiovascular imaging techniques. The primary diagnostic methods for CAD include electrocardiography (ECG), biochemical markers, echocardiography, stress tests, computed tomography angiography (CTA), and invasive coronary angiography. The severity of the disease determines the necessity for CABG, the extent of vascular involvement, and the clinical condition of the patient [18].

Most patients present with chest pain (angina pectoris), which is typically described as a pressure-like discomfort behind the sternum that occurs with exertion. In stable angina, the pain is usually short-lived and resolves with rest or the administration of nitroglycerin. In contrast, unstable angina is associated with acute myocardial ischemia, lasts longer, and may occur even at rest [18]; the pain often radiates to the left arm, neck, jaw, or back.

As CAD progresses, symptoms such as dyspnea, decreased exercise capacity, fatigue, and syncope may also be observed. Meanwhile, signs of heart failure may become more prominent in advanced-stage patients with impaired left ventricular function; paroxysmal nocturnal dyspnea, orthopnea, and lower extremity edema are common clinical findings in these patients [19].

An ECG is the first-line diagnostic tool, particularly in patients suspected of having acute coronary syndrome, as it allows for the evaluation of myocardial ischemia findings. Meanwhile, ST-segment elevation, depression, or T-wave inversion are important indicators of ischemic changes. However, in stable CAD patients, ECG findings may be normal or show nonspecific changes [18].

Biochemical markers play a critical role in identifying myocardial injury, and cardiac biomarkers, such as troponin I and troponin T, are the most sensitive and specific indicators of myocardial necrosis. High-sensitivity troponin assays are particularly valuable for the early diagnosis of acute coronary syndrome. Additionally, biomarkers such as CRP and NT-proBNP are useful in detecting inflammation and the presence of heart failure [18].

Echocardiography is a vital imaging modality used in CAD patients to assess left ventricular function and detect segmental wall motion abnormalities resulting from ischemic heart disease. Stress echocardiography is beneficial for determining myocardial perfusion and the presence of ischemia and is often utilized for risk stratification in asymptomatic patients or those with atypical symptoms [19].

Functional stress tests are noninvasive methods used to evaluate myocardial ischemia. The exercise stress test provides an assessment of exercise capacity, and when combined with myocardial perfusion scintigraphy or stress echocardiography, this test offers higher sensitivity in identifying ischemic regions [19]. Comparatively, pharmacological stress tests using dobutamine or adenosine are preferred in patients with limited exercise capacity.

CTA is an advanced imaging modality that enables noninvasive anatomical evaluation of the coronary arteries. CTA is particularly useful in patients with low to moderate risk for detecting the presence, extent, and calcification of atherosclerotic plaques. However, in advanced CAD and cases with extensive multivessel involvement, the diagnostic accuracy of CTA may be limited [19].

Thus, coronary angiography remains the gold standard diagnostic method for patients requiring CABG, as it allows for the precise assessment of the severity and extent of coronary artery stenosis. Despite being an invasive procedure, coronary angiography is the most reliable technique for determining the necessity of CABG, especially in patients with triple-vessel disease, left main coronary artery disease, or high-risk symptomatic lesions [18].

The SYNTAX score is a classification system used to evaluate the extent and complexity of coronary artery disease. Studies have demonstrated that in patients with high SYNTAX scores, CABG is superior to PCI in reducing long-term mortality and morbidity [20].

In conclusion, before CABG is indicated, a detailed clinical assessment should be performed using functional tests and advanced imaging techniques to ensure the most accurate diagnosis. The symptoms, biochemical markers, and anatomical evaluation results of each patient should be considered collectively to determine the most appropriate treatment strategy.

Therapeutic Approaches

The treatment approaches for CAD are determined based on the extent of the disease, the severity of symptoms, and the overall health status of the patient. Treatment options include medical therapy, PCIs, and surgical revascularization methods. CABG is considered the most effective treatment for patients with triple-vessel disease, left main CAD, and complex lesions [21].

Medical therapy is a cornerstone of CAD management and includes anti-ischemic, antithrombotic, and lipid-lowering treatments. Beta-blockers reduce myocardial oxygen consumption, alleviating anginal symptoms, while calcium channel blockers and long-acting nitrates enhance coronary vasodilation, improving myocardial perfusion [9]. Statins lower LDL levels, slowing the progression of atherosclerotic plaques and reducing the risk of cardiovascular events. Additionally, in high-risk patients, antiplatelet therapy with low-dose aspirin and P2Y12 inhibitors (clopidogrel, prasugrel, ticagrelor) is commonly used [12].

PCIs are an effective treatment option, particularly for patients with isolated lesions or low SYNTAX scores. Modern drug-eluting stents (DESs) have significantly reduced restenosis rates, thereby improving long-term graft patency. However, in patients with extensive and complex CAD, CABG has been associated with superior long-term survival and lower rates of repeat revascularization compared to PCIs [20].

CABG remains the most effective revascularization method for severe CAD. During the CABG procedure, arterial or venous grafts are used to restore blood flow to the distal coronary arteries affected by atherosclerosis. The left internal mammary artery (LIMA) is the preferred graft due to its superior long-term patency rates. Radial artery and right internal mammary artery grafts are alternative arterial conduits that offer better long-term outcomes than venous grafts [5]. Saphenous vein grafts (SVGs) are used when arterial grafts are insufficient; however, these grafts have a higher rate of occlusion.

CABG procedures can be performed with or without cardiopulmonary bypass (CPB). The conventional on-pump CABG technique provides a stable surgical field but may increase the inflammatory response and lead to neurological complications. Off-pump CABG has the potential to reduce these complications and is preferred in high-risk patients [7]. MICS-CABG eliminates the need for sternotomy, facilitating faster patient recovery, while advancements such as robotic-assisted CABG hold promise for further improving surgical outcomes [6]. Robotic-assisted techniques are broadly categorized into two main types: Robotically assisted minimally invasive direct coronary artery bypass (RA-MIDCAB) and totally endoscopic coronary artery bypass (TECAB). In the RA-MIDCAB, robotic arms assist the surgeon in harvesting the internal mammary artery and performing direct anastomosis through a mini-thoracotomy, typically without the need for cardiopulmonary bypass (Fig. 1, Ref. [10]). In contrast, TECAB is performed entirely endoscopically without opening the chest cavity, often requiring advanced robotic dexterity and perfusion strategies such as femoral cannulation for cardiopulmonary support. While TECAB offers the benefit of being completely incisionless at the sternum, it is associated with longer operative times and a steep learning curve, thereby limiting its widespread adoption [6]. Nonetheless, these techniques may result in longer operative and CPB times, particularly in the hands of less experienced teams.

Hybrid revascularization strategies combine surgical and percutaneous interventions, which is particularly useful in high-risk patients or those with multivessel disease, where surgical intervention is beneficial for one lesion while PCI is more suitable for others. For example, LIMA-to-LAD anastomosis can be performed via CABG, while other lesions are treated using PCIs [8]. Despite its conceptual advantages, hybrid revascularization remains an area of limited high-quality evidence. In a large-scale observational study, Hannan *et al*. [22] compared hybrid coronary revascularization with conventional CABG and reported that while hybrid procedures were associated with lower short-term complication rates, these procedures were also linked to higher long-term mortality and repeat revascularization rates. These findings underscore the need for careful patient selection and highlight that hybrid strategies may not yet offer consistent long-term benefits over conventional CABG in the general population [22].

In conclusion, the treatment approach for CAD is determined based on the clinical condition of the patient and the extent of the disease (Table 3, Ref. [5–10,12,16,20–26]). While medical therapy slows disease progression and

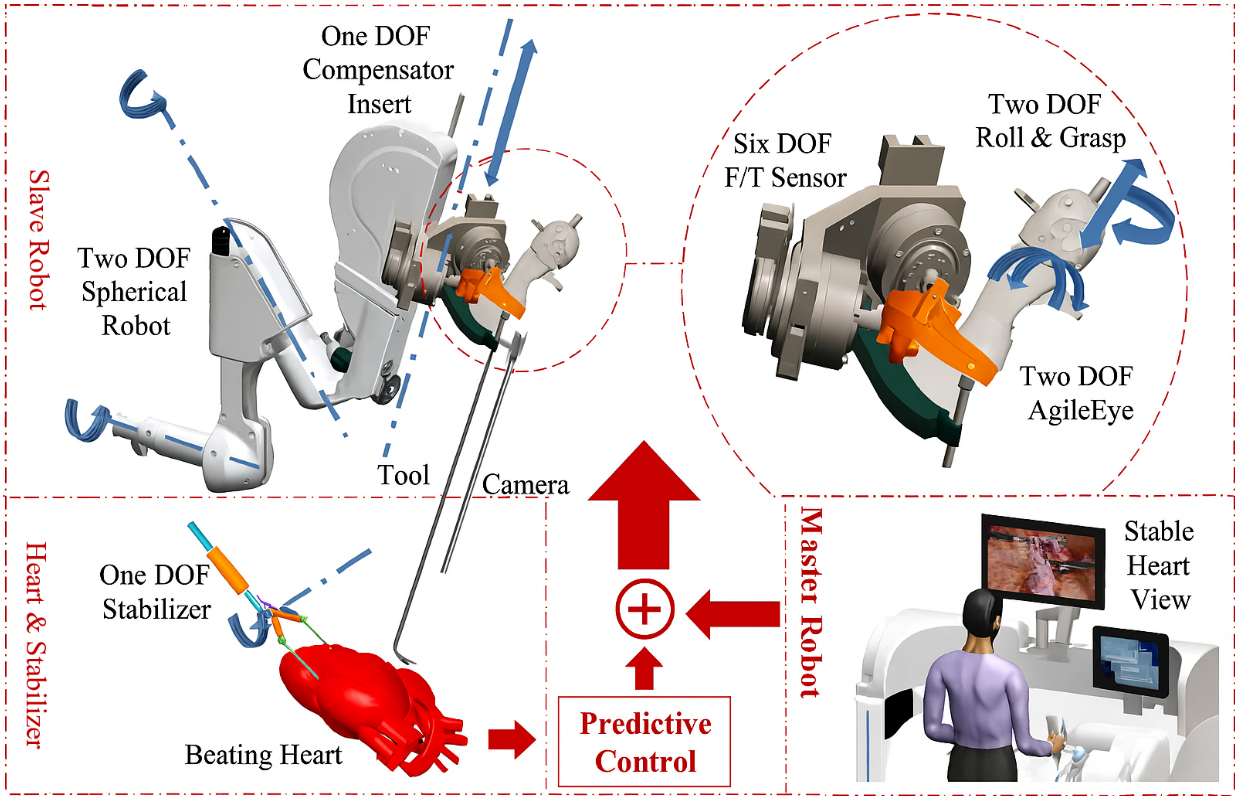

Fig. 1. Overview of a master–slave robotic setup used for robotic-assisted coronary bypass surgery. The system enables precise manipulation via a control console, robotic arm with multiple degrees of freedom (DOF), and predictive control algorithms for stabilizing the beating heart [10].

Table 3. Therapeutic approaches in coronary artery disease (CAD) management.

Approach	Description	Supporting evidence
Medical therapy	Includes antiplatelets, statins, beta-blockers, and RAAS inhibitors.	[9,12]
Percutaneous coronary intervention (PCI)	A less invasive procedure, which is suitable for isolated lesions, and uses drug-eluting stents.	[20,21]
Conventional CABG	Gold standard for multivessel disease and provides long-term patency.	[5,21]
Off-pump CABG	Avoids CPB and reduces neurological and inflammatory complications.	[7,16]
Minimally invasive CABG	Uses small thoracotomy incisions and facilitates faster recovery.	[6,24]
RA-MIDCAB	Robotic-assisted LIMA-to-LAD anastomosis via mini-thoracotomy; off-pump.	[6]
TECAB	Totally endoscopic robotic CABG, requires advanced skills and longer CPB time.	[6,25]
Robotic-assisted CABG	Enhances precision with robotic systems and reduces hospital stay.	[6,10]
Multiple arterial grafting	Use of more than one arterial conduit (e.g., LIMA + radial), improves patency.	[5,23]
Hybrid revascularization	Combines CABG and PCI for selected patient populations.	[8,22]
Bioengineered grafts	Experimental tissue-engineered vascular conduits for future applications.	[25,26]

CABG, Coronary artery bypass grafting; PCI, Percutaneous coronary intervention; CPB, Cardiopulmonary bypass; RAAS, Renin–angiotensin–aldosterone system; RA-MIDCAB, Robotically assisted minimally invasive direct coronary artery bypass; TECAB, Totally endoscopic coronary artery bypass; LIMA, Left internal mammary artery; LAD, Left anterior descending artery.

PCI provides successful revascularization in select cases, CABG remains the most effective treatment for patients with complex CAD, improving long-term survival. Moreover, with ongoing advancements in surgical techniques and revascularization strategies, CABG is expected to become even safer and more effective in the future. In recent years, AI-based decision support systems have gained increasing relevance in the management of coronary artery disease and surgical planning. These technologies utilize machine learning algorithms trained on large clinical datasets to assist in preoperative evaluation, graft selection, and intraoperative guidance (Fig. 2, Ref. [27]). In CABG,

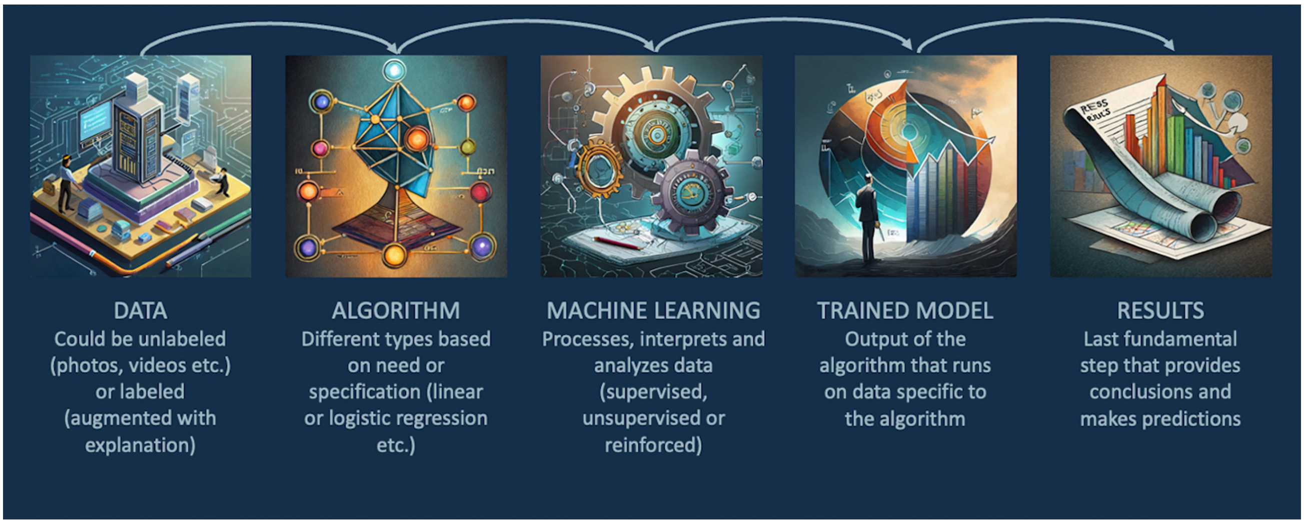

Fig. 2. The process begins with the input of clinical and imaging data, followed by algorithmic processing using machine learning techniques. Trained models then generate personalized outputs, including graft selection recommendations, risk stratification, and predicted outcomes such as graft patency or mortality [27].

AI tools can reconstruct patient-specific three-dimensional (3D) coronary anatomy, simulate different grafting strategies, and predict outcomes such as graft patency, mortality, and risk of complications. The integration of these systems into surgical practice not only enables personalized conduit selection but also enhances surgical precision, particularly in cases of complex multivessel disease. Moreover, AI is expected to play a transformative role in optimizing CABG outcomes as it continues to evolve [27].

Treatment Monitoring and Medication Management

Postoperative management and medication therapy following CABG are of critical importance in maintaining successful surgical outcomes and reducing the risk of long-term complications. Thus, a multidisciplinary approach is required to ensure hemodynamic stability, preserve graft patency, and prevent ischemic events in the postoperative period [28].

Continuous monitoring of cardiac function is essential in the follow-up process. Therefore, echocardiography is commonly used to assess left ventricular ejection fraction and myocardial contractility. Meanwhile, cardiac biomarkers, particularly troponin levels, aid in evaluating myocardial injury following surgery [28]. Noninvasive stress testing or coronary CTA can be utilized to assess graft patency, although invasive coronary angiography may be necessary in cases of recurrent ischemic symptoms [29].

Medication management plays a vital role in reducing postoperative mortality and morbidity. Antiplatelet therapy is a standard practice for preventing graft occlusion, with aspirin recommended for initiation in the early postoperative period and continued lifelong use. In patients with saphenous vein grafts, P2Y12 inhibitors (such as clopidogrel, prasugrel, or ticagrelor) may be added as short-term adjunctive therapy [30].

Statins therapy is routinely implemented to stabilize atherosclerotic plaques and improve graft patency rates. High-dose statins, such as atorvastatin or rosuvastatin, effectively lower LDL levels, preventing restenosis. Additionally, their anti-inflammatory properties contribute to reducing postoperative cardiovascular complications [9].

Beta-blockers reduce myocardial oxygen consumption, decrease cardiac workload, and lower the risk of postoperative arrhythmias. Thus, beta-blockers are particularly recommended for patients with reduced ejection fraction due to their mortality-reducing effects. Meanwhile, renin–angiotensin–aldosterone system (RAAS) inhibitors are prescribed to prevent left ventricular remodeling, especially in patients with hypertension or diabetic nephropathy [9].

Postoperative antiarrhythmic therapy is crucial, particularly for managing atrial fibrillation, a common arrhythmia after CABG—amiodarone or beta-blockers are effective in controlling such arrhythmias. Additionally, postoperative hypertension should be carefully managed with appropriately selected antihypertensive agents to create an individualized treatment plan [30].

Another key aspect of postoperative care is the management of diabetes mellitus. Proper glycemic control in diabetic patients accelerates wound healing and reduces the risk of infection. Intensive insulin therapy may be employed to manage hyperglycemia, although careful glucose monitoring is necessary to minimize the risk of hypoglycemia [9].

In conclusion, postoperative management and medication therapy after CABG should be meticulously implemented to maximize surgical success and prevent long-term complications. Pharmacological agents, including antiplatelet therapy, statins, beta-blockers, and RAAS inhibitors, are essential in maintaining graft patency and supporting myocardial function. Regular clinical evaluation and personalized medication management in the postoperative period play a crucial role in improving long-term survival rates.

Discussion

CABG is considered one of the most effective surgical revascularization methods for patients with extensive and severe CAD. In recent years, several innovative approaches have been developed to improve CABG outcomes, including the use of arterial grafts, minimally invasive techniques, robotic-assisted surgery, modifications in cardiopulmonary bypass techniques, and pharmacological therapies. Current literature has extensively analyzed the efficacy of conventional CABG methods compared to these newer techniques, highlighting their advantages and limitations.

The type of graft used in CABG is one of the most critical factors that influences long-term surgical success. Studies have shown that the left internal mammary artery has significantly higher long-term patency rates compared to venous grafts [23]. A large-scale study by Ren *et al.* [24] reported that the 8-year patency rate of LIMA grafts reached 93%, whereas this rate dropped to approximately 72% for SVGs.

Radial artery grafts are commonly used when the LIMA is insufficient or when additional revascularization is required. The Radial Artery Patency Study (RAPS) demonstrated that radial arteries have lower occlusion rates than SVGs over a five-year period [31]. However, due to their tendency for vasospasm and potential impact on distal perfusion, careful patient selection is essential for optimal outcomes with radial artery grafts.

Conversely, SVGs remain widely used, particularly in cases requiring long-segment bypass grafting. However, due to endothelial damage, progressive atherosclerosis, and a high risk of thrombosis, venous grafts have lower patency rates compared to arterial grafts [21]. To improve SVG outcomes, proper endothelial preservation during graft preparation and meticulous postoperative antiplatelet therapy are recommended [30].

MICS-CABG is a technique that utilizes small thoracotomy incisions instead of conventional median sternotomy. This method has the potential to reduce sternotomy-related complications, shorten hospital stays, and accelerate recovery. A study by Guangxin *et al.* [31] demonstrated that patients undergoing MICS-CABG had significantly shorter hospital stays and lower transfusion requirements, highlighting the perioperative advantages of minimally invasive techniques. However, the study also reported comparable 5-year graft patency rates between MICS-CABG and conventional CABG in low-to-intermediate-risk patients [31], suggesting that while MICS-CABG may offer enhanced recovery, it does not confer a long-term patency advantage over traditional approaches. Therefore, the choice between MICS-CABG and conventional CABG should be based on individual patient risk profiles and institutional expertise, rather than assumptions of long-term superiority [31].

The applicability of minimally invasive approaches depends on the expertise of the surgeon and patient selection criteria. While MICS-CABG provides favorable outcomes in low-risk patients, conventional sternotomy remains the gold standard for achieving complete revascularization in patients with multivessel disease [25]. In complex cases, minimally invasive techniques may pose technical challenges and limit the completeness of revascularization [6].

Robotic-assisted surgery, particularly using the da Vinci Surgical System, has gained increased attention in CABG procedures since this technique allows for smaller incisions and provides surgeons with enhanced precision during anastomosis [8]. Comparatively, both RA-MIDCAB and TECAB have demonstrated favorable short-term outcomes, including reduced postoperative pain, quicker ambulation, and lower infection rates. However, TECAB remains less commonly performed due to the requirement for advanced robotic training and prolonged aortic endo-occlusion times. Alternatively, RA-MIDCAB is more widely adopted and has been reported to achieve graft patency rates comparable to conventional CABG, particularly in single-vessel LAD revascularization. Nevertheless, neither approach has consistently shown superiority in long-term outcomes over traditional techniques, and their use remains highly dependent on surgeon experience and institutional resources [6,8]. Compared to conventional surgery, robotic CABG offers advantages such as reduced tissue trauma, shorter hospital stays, and decreased postoperative pain [25]. However, robotic CABG—particularly TECAB—is often associated with longer CPB duration, extended operative and anesthesia times, and previously noted aortic endo-occlusion requirements compared to conventional methods. These factors may lead to longer mechanical ventilation times and a moderate increase in hospital stay, particularly during the early stages of the learning curve. Additionally, the cost of equipment, its availability, and the need for a highly experienced surgical team further limit its widespread implementation [6,8,26]. The high initial investment required for robotic systems, including acquisition, maintenance, and training costs, presents a significant barrier to adoption, especially in centers with limited resources. Furthermore, robotic CABG procedures involve a steep learning curve, often requiring extensive hands-on training and high case volumes to achieve proficiency. In many institutions, the lack of a dedicated robotic surgery team and limited patient volume further hinders program development. These challenges not only impact procedural safety and efficiency during the early adoption phase but also limit equitable access to robotic revascularization in broader clinical settings [6,8,26].

However, studies comparing robotic CABG with conventional techniques have not demonstrated significant differences in long-term graft patency rates [26]. Another area of ongoing debate in the literature is the long-term clinical superiority of robotic and off-pump CABG compared to conventional techniques. While short-term outcomes such as reduced blood loss, shorter ICU stay, and fewer wound complications are consistently reported, evidence on long-term mortality, myocardial infarction, and graft patency remains inconclusive. Additionally, meta-analyses and large cohort studies often yield conflicting results, underscoring the need for standardized, multicenter, randomized trials to inform surgical decision-making [8,23]. A study by Dokollari *et al*. [26] found that five-year graft patency rates were similar between robotic CABG and traditional open surgery. Additionally, the high costs, steep learning curve, and limited availability of robotic systems are factors that hinder widespread adoption of this approach [8].

One of the major concerns surrounding robotic CABG is its ability to achieve complete revascularization. While conventional CABG allows for multivessel bypass grafting more easily, robotic procedures face anatomical limitations that may restrict the complexity of operations. Moreover, the success of robotic surgery is directly linked to the experience of the surgeon and the coordination of the surgical team [26].

CPB remains a fundamental component of conventional CABG, ensuring hemodynamic stability during surgery; however, CPB is associated with systemic inflammatory responses, which can contribute to postoperative organ dysfunction [1]. For this reason, some surgeons prefer OPCAB, a technique performed without the use of CPB.

Compared to conventional CABG, OPCAB has been associated with reduced postoperative inflammation and lower rates of neurological complications [26]. However, studies have suggested that OPCAB may have lower long-term graft patency rates than CPB-assisted techniques [7]. The technical complexity of maintaining hemodynamic stability in OPCAB and its potential impact on anastomosis quality are key limitations restricting its widespread use, particularly in high-risk patients [32].

The cornerstone of durable success in CABG surgery is achieving high graft patency rates. Numerous studies have demonstrated that long-term graft patency is the single most predictive factor for both symptom-free survival and reduced need for repeat interventions. Therefore, strategies to improve patency, including optimal conduit selection, meticulous anastomosis techniques, and pharmacologic graft protection, must be central to surgical planning [5,24]. Despite their long-term advantages, arterial grafts have certain limitations: The number of arterial conduits is limited, particularly in older patients or those with comorbidities that affect the peripheral vasculature. Harvesting arterial grafts, such as the radial or gastroepiploic artery, requires additional operative time and presents risks, including vasospasm, injury to surrounding structures, or impaired perfusion to the donor sites. Moreover, technical expertise is necessary to avoid complications and ensure optimal flow dynamics. These factors may restrict the routine use of multiple arterial grafts in all patients, necessitating individualized graft planning [5,24,31]. One of the most crucial factors for CABG success is the selection of appropriate patients. Variables such as age, ventricular function, comorbidities (e.g., diabetes mellitus, renal insufficiency), and coronary anatomy significantly affect the choice of technique and conduit. Equally important is perioperative management, including hemodynamic optimization, graft preservation strategies, and pharmacological support. These components not only reduce perioperative risk but also ensure graft longevity and improve long-term prognosis. The integration of emerging techniques into CABG practice must be carefully considered based on patient-specific clinical characteristics. For instance, older patients or those with significant comorbidities may benefit from off-pump or minimally invasive techniques due to reduced perioperative risk. In contrast, younger and low-risk patients may be more appropriate candidates for multiple arterial grafting strategies aimed at optimizing long-term patency. The choice of surgical approach should therefore be individualized, considering not only coronary anatomy but also functional status, comorbidities, and the availability of surgical technologies at the institution. CABG surgery now incorporates various techniques and graft options, making individualized surgical planning crucial for optimizing outcomes. The use of arterial grafts, particularly LIMA and radial artery grafts, has demonstrated superior long-term patency rates compared to venous grafts [5]. Thus, while minimally invasive and robotic-assisted approaches offer potential benefits for postoperative recovery, conventional CABG remains the gold standard for multivessel disease [25,26].

Recent developments in tissue engineering and regenerative medicine have introduced bioengineered vascular grafts as a potential alternative in CABG, particularly when autologous conduits are unavailable or inadequate. These grafts are typically composed of biodegradable scaffolds seeded with endothelial cells or smooth muscle cells, aiming to mimic the structural and functional properties of native vessels. In preclinical studies, such constructs have shown promising results in terms of patency, endothelialization, and resistance to thrombosis [33]. However, challenges such as mechanical stability, immune compatibility, and long-term durability remain to be addressed before routine clinical application can be achieved [33,34]. Future advancements in bioengineering, artificial vascular grafts, and genetic modifications may further improve CABG outcomes [32,33]. AI is increasingly being integrated into cardiovascular surgical practice, particularly in preoperative planning, risk prediction, and intraoperative decision support. Machine learning algorithms trained on large-scale surgical datasets can predict graft patency, risk of reintervention, and postoperative complications, enabling more precise and personalized operative strategies [35]. Furthermore, AI-powered 3D modeling and simulation tools are being utilized to guide conduit selection and optimize graft positioning, particularly in cases of complex multivessel disease. While still in early phases of adoption, these technologies are expected to become central to next-generation surgical planning [35]. AI-assisted surgical planning and intraoperative imaging technologies may enhance precision in anastomosis, ultimately improving graft success rates [35]. These developments are expected to make CABG an even safer, more effective, and highly individualized procedure in the years to come. In the near future, it is anticipated that machine learning algorithms will play a more significant role in preoperative risk stratification, graft selection, and the prediction of graft failure. Additionally, 3D printing technologies and biologically engineered grafts may revolutionize complex revascularization cases where conventional conduits are insufficient. As these technologies evolve, multidisciplinary collaboration among surgeons, biomedical engineers, and data scientists will be essential for the safe and effective translation of clinical applications.

Limitations

This article presents a narrative review that examines the historical evolution, surgical techniques, graft selection, and postoperative outcomes of CABG. As such, this review does not follow the rigorous protocols of a systematic review or meta-analysis. Although a specific methodology was applied in the literature selection process, standard systematic review protocols, including predefined inclusion and exclusion criteria and quantitative synthesis methods, were not utilized. This may have introduced selection bias and limited the inclusion of potentially contradictory evidence. Additionally, heterogeneity among the included studies in terms of patient demographics, surgical techniques, and outcome measures limits the generalizability of the conclusions.

Another important limitation is the scarcity of robust long-term outcome data for many of the newer and evolving surgical techniques, such as robotic-assisted CABG, minimally invasive procedures, and bioengineered vascular grafts. While these innovations offer promising advantages, the lack of large-scale, long-term randomized trials prevents definitive conclusions regarding their routine integration into clinical practice.

Furthermore, studies evaluating graft patency rates often vary significantly across different patient populations and clinical settings, making it difficult to establish standardized graft selection criteria. The same applies to comparative data between minimally invasive and conventional CABG approaches, where long-term efficacy and safety remain incompletely defined.

Lastly, while this review touches on the comparison between CABG and PCIs, available evidence remains limited in terms of head-to-head, long-term trials across diverse patient subgroups. Hence, further large-scale, randomized studies are needed to clarify the most appropriate revascularization strategy for individualized patient care.

Future studies should focus on addressing the existing evidence gaps identified in this review. In particular, well-designed randomized controlled trials are needed to evaluate the long-term clinical efficacy and patency outcomes of minimally invasive and robotic-assisted CABG techniques in high-risk populations. Additionally, the clinical performance of bioengineered vascular grafts in specific patient groups, such as individuals with diabetes mellitus, remains largely unexplored and warrants focused investigation. The role of AI in surgical planning and intraoperative guidance also presents a promising field of research, particularly in improving conduit selection and perioperative risk prediction for complex multivessel disease.

Conclusions

CABG remains the most effective revascularization strategy for patients with multivessel disease and anatomically complex coronary lesions. Among all graft options, arterial grafts—particularly the LIMA—consistently demonstrate superior long-term patency and improved survival outcomes compared to venous grafts. Although minimally invasive and robotic-assisted techniques show promise in enhancing recovery and cosmetic outcomes, conventional CABG continues to serve as the gold standard due to its proven efficacy and durability.

Looking ahead, emerging innovations such as AI-assisted surgical planning, bioengineered vascular grafts, and advanced intraoperative imaging hold great potential for optimizing CABG outcomes. Among these, AI-based systems currently possess the highest clinical applicability and are already being utilized in risk stratification, conduit selection, and intraoperative decision-making at select centers. In contrast, limitations remain in robotic and minimally invasive techniques due to cost, learning curve, and limited availability. Bioengineered vascular grafts, though promising in preclinical models, remain experimental and are not yet ready for routine clinical integration. Therefore, these technologies must be evaluated based on institutional capabilities and patient-specific characteristics.

From a clinical perspective, the LIMA should remain the first-line conduit, particularly for revascularization of the left anterior descending artery. In situations where the LIMA is contraindicated, such as prior thoracic surgery, radiation exposure, or subclavian artery stenosis, alternative arterial grafts, including the radial artery or the right internal mammary artery, should be considered as alternatives. SVGs, while widely used, should be viewed as secondary options due to their relatively lower long-term patency. Lastly, the selection of surgical technique, whether conventional or minimally invasive, must be tailored to both patient-specific anatomical considerations and institutional expertise, emphasizing the importance of individualized surgical planning and optimal perioperative management to achieve the best long-term outcomes.

Abbreviations

CABG, Coronary Artery Bypass Grafting; CAD, Coronary Artery Disease; LIMA, Left Internal Mammary Artery; SVG, Saphenous Vein Graft; MICS-CABG, Minimally Invasive Coronary Artery Bypass Grafting; OP-CAB, Off-Pump Coronary Artery Bypass; PCI, Percutaneous Coronary Intervention; AI, Artificial Intelligence; CPB, Cardiopulmonary Bypass; RCT, Randomized Controlled Trial; EF, Ejection Fraction; CRP, C-Reactive Protein; LDL, Low-Density Lipoprotein; RCT, Randomized Controlled Trial; SYNTAX Score, Synergy Between PCI With Taxus and Cardiac Surgery Score; RCT, Randomized Controlled Trial.

Author Contributions

Both authors (AB and BT) contributed equally to the conception, design, data acquisition, analysis, and interpretation of the work. They were both involved in drafting, revising, and critically reviewing the manuscript, and have approved the final version for submission and publication. Both authors agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

The authors declare no conflict of interest.

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