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State of the Art Off-Pump Coronary Artery Bypass Grafting

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ABSTRACT

Off-pump coronary artery bypass grafting (OPCAB) has evolved into a mature and reproducible strategy for myocardial revascularization. Although conventional on-pump coronary artery bypass grafting (ONCAB) became the standard approach with the advent of cardiopulmonary bypass (CPB), advances in cardiac stabilization, positioning, intracoronary shunting, and anesthetic management have enabled complete multivessel revascularization on the beating heart without CPB. Clinical studies have shown that OPCAB achieves outcomes comparable to ONCAB in appropriately selected patients while reducing several CPB-related complications, particularly in high-risk populations. However, long-term success depends on surgeon expertise, institutional experience, and complete revascularization. Emerging technologies, including minimally invasive, robotic-assisted, and hybrid coronary procedures, continue to expand the role of beating-heart surgery. This review summarizes the evolution, evidence, indications, limitations, and future directions of OPCAB as an important complementary strategy in contemporary coronary revascularization.

Keywords: Cardiopulmonary Bypass. Coronary Artery Bypass. Coronary Artery Disease. Off-Pump Coronary Artery Bypass. Treatment Outcome.

Abbreviations, Acronyms & Symbols	
CABG	= Coronary artery bypass grafting
CPB	= Cardiopulmonary bypass
LAD	= Left anterior descending artery
ONCAB	= On-pump coronary artery bypass grafting
OPCAB	= Off-pump coronary artery bypass grafting
RCTs	= Randomized controlled trials

INTRODUCTION

Coronary artery bypass grafting (CABG) originated as a beating-heart operation performed before the development of cardiopulmonary bypass (CPB). Early pioneers demonstrated that direct coronary revascularization was feasible despite the absence of cardiac stabilizers, intracoronary shunts, and suction positioners. Although technically successful, these procedures were difficult to reproduce and therefore remained limited in application.

The introduction of CPB and reliable myocardial protection transformed coronary surgery by providing a motionless, bloodless operative field. These advantages facilitated complex multivessel revascularization and established conventional on-pump CABG (ONCAB) as the standard treatment for coronary artery disease for several decades.

Interest in beating-heart surgery re-emerged during the 1980s through the pioneering work of Buffolo and colleagues, in Brazil, and Benetti, in Argentina, who independently demonstrated that CABG could be safely performed without CPB. Subsequent innovations in cardiac positioning, coronary stabilization, intracoronary shunting, and anesthetic management enabled complete multivessel revascularization on the beating heart, transforming off-pump CABG (OPCAB) into a reproducible surgical strategy.

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Today, OPCAB is an established component of contemporary coronary surgery. Randomized trials, observational studies, and meta-analyses have shown that, when performed by experienced surgeons, OPCAB provides clinical outcomes comparable to ONCAB while reducing systemic inflammatory response and selected complications associated with CPB, including transfusion requirements, atrial fibrillation, renal dysfunction, and stroke in high-risk patients. However, outcomes remain highly dependent on surgeon experience, institutional volume, and the ability to achieve complete revascularization. This review provides a contemporary overview of OPCAB, focusing on its evolution, clinical evidence, current indications, and emerging role in minimally invasive and hybrid coronary revascularization.

EARLY PIONEERS OF BEATING-HEART CORONARY SURGERY

The first successful attempts at direct surgical myocardial revascularization were reported in the early 1960s by Goetz and colleagues[1] performing the first successful internal mammary artery-to-coronary artery anastomosis using a tantalum-ring mechanical connector rather than conventional sutures. Subsequently, Kolesov and Potashov reported their pioneering experience with internal mammary artery grafting to the left anterior descending artery (LAD) on the beating heart, first in Russia, in 1965[2], and later in the United States of America, in 1967[3]. These operations were performed through left thoracotomy and, in some cases, employed mechanical anastomotic devices. Remarkably, they were undertaken before the routine use of coronary angiography, with patient selection based primarily on clinical assessment.

Additional clinical series were independently reported by Trapp and Bysaria, in Canada[4], and by Ankeney, in the United States of America[5]. Although these early experiences demonstrated the feasibility of beating-heart coronary surgery, the technique failed to gain widespread acceptance.

THE CARDIOPULMONARY BYPASS ERA

The introduction and rapid evolution of CPB fundamentally changed the landscape of coronary surgery. By providing a motionless, bloodless operative field, together with reliable myocardial protection, conventional CABG enabled surgeons to perform precise coronary anastomoses and achieve complete myocardial revascularization, even in patients with complex multivessel coronary artery disease. The widespread adoption of CABG was driven by the pioneering work of René Favaloro[6] and Dudley Johnson[7], who standardized the use of saphenous vein grafts in conjunction with CPB. As a result, ONCAB became the gold standard for surgical myocardial revascularization for more than three decades.

REVIVAL OF OFF-PUMP CORONARY SURGERY

Interest in beating-heart coronary surgery re-emerged during the 1980s and early 1990s. Buffolo, in Brazil[8], and, independently, Benetti, in Argentina[9], reported consecutive series of patients undergoing CABG using saphenous vein and internal mammary artery grafts without CPB. Their work demonstrated that safe and effective myocardial revascularization could be achieved on the beating heart and stimulated renewed interest in the technique.

Additional clinical experience was subsequently reported by Archer[10], Laborde[11], and others.

Early refinements included improved patient positioning, advances in anaesthetic management, and pharmacological heart-rate control using β-blockers and calcium-channel blockers. However, exposure remained limited, restricting OPCAB largely to the anterior and main right coronary artery, while revascularization of the lateral and posterior walls remained technically demanding.

OVERCOMING TECHNICAL LIMITATIONS

A breakthrough occurred in 1993 when Ricardo Lima[12] introduced the posterior pericardial traction suture, subsequently known as the *Lima stitch*. By safely elevating and rotating the heart while preserving hemodynamic stability, this technique provided reliable exposure of the lateral, inferior, and posterior coronary arteries. For the first time, complete multivessel myocardial revascularization without CPB became technically feasible and reproducible.

Building on the pioneering work of Buffolo, Benetti, and Lima[8,9,12], José Glauco Lobo Filho[13] demonstrated that complete multivessel myocardial revascularization could be safely achieved without CPB in > 90% of patients. This milestone established OPCAB as a practical strategy for routine complete coronary revascularization rather than a procedure reserved for selected cases.

EVOLUTION OF CARDIAC EXPOSURE AND STABILIZATION

The success of OPCAB paralleled the development of increasingly sophisticated techniques for cardiac exposure and stabilization. Early procedures relied on manual cardiac displacement, folded gauze pads, and simple pericardial traction sutures, which, although effective, were technically demanding and generally limited to anterior coronary vessels.

During the modern era, Buffolo and Benetti[8,9] refined beating-heart surgery using temporary coronary occlusion with silicone vessel loops or tourniquets to create a bloodless operative field, together with pharmacological heart-rate control to reduce cardiac motion. Subsequently, Rivetti and Gandra[14] introduced the intracoronary shunt, allowing continuous distal coronary perfusion during construction of the anastomosis and reducing regional myocardial ischemia.

Lima et al.[15] posterior pericardial traction suture represented the pivotal advance in cardiac positioning, enabling consistent exposure of all coronary territories. Bergsland et al.[16] later simplified the technique by demonstrating that a single posterior pericardial suture could achieve comparable exposure while maintaining hemodynamic stability.

These physiological and technical advances provided the foundation for the development of dedicated compression- and suction-based coronary stabilizers and apical suction positioners[17-19]. By selectively immobilizing the target vessel while preserving global cardiac motion, these devices enabled precise and reproducible coronary anastomoses, transforming OPCAB into a standardized and widely reproducible technique.

Today, modern OPCAB combines optimized cardiac positioning, coronary stabilizers, apical suction devices, intracoronary shunts, blower-mister systems, and continuous hemodynamic monitoring into an integrated operative platform capable of achieving complete myocardial revascularization without CPB.

ANESTHETIC MANAGEMENT

Successful OPCAB depends as much on anaesthetic expertise as on surgical technique. Unlike conventional CABG, the anesthesiologist must maintain hemodynamic stability while the beating heart is displaced to expose different coronary territories. Careful optimization of preload, vasoactive support, heart rate, invasive monitoring, and transesophageal echocardiography, when available, is essential to detect and correct hemodynamic compromise. Appropriate ventilatory strategies, including low tidal-volume ventilation and individualized positive end-expiratory pressure, facilitate surgical exposure while maintaining adequate oxygenation.

Close coordination between surgeons, anesthesiologists, perfusionists, and the entire operating room team is fundamental to procedural success. Structured training, multidisciplinary teamwork, and institutional experience remain key determinants of the safety and reproducibility of OPCAB[20,21].

MINIMALLY INVASIVE AND HYBRID CORONARY REVASCULARIZATION

The persistence of pioneering OPCAB surgeons ultimately led to the development of minimally invasive coronary surgery. Benetti introduced left internal mammary artery-to-LAD grafting through a small left thoracotomy, later termed minimally invasive direct coronary artery bypass[22,23]. The technique was subsequently popularized by Benetti, Calafiore, and Salerno as the left anterior small thoracotomy approach[24].

These innovations laid the foundation for hybrid coronary revascularization first proposed by the Bristol group, combining the long-term durability of a left internal mammary artery-to-LAD graft with percutaneous coronary intervention for non-LAD lesions, thereby achieving complete revascularization through a less invasive strategy[25-28].

SURGICAL TRAINING AND INSTITUTIONAL EXPERIENCE

The technical complexity of OPCAB has transformed surgical education, requiring structured, competency-based training beyond the traditional apprenticeship model. Unlike conventional CABG, OPCAB demands simultaneous mastery of cardiac positioning, coronary stabilization, precise coronary anastomosis, and continuous hemodynamic management. Contemporary training follows stepwise progression from anterior to more technically challenging coronary territories, allowing surgeons to safely acquire increasingly complex skills. Simulation-based education, including beating-heart simulators and virtual reality platforms, further accelerates technical proficiency and shortens the learning curve before independent practice. Institutional experience remains a major determinant of outcomes, with high-volume centers consistently achieving lower mortality, fewer complications, and more complete revascularization. Consequently, dedicated training programs, mentorship, and centers of excellence have become essential for successful OPCAB implementation. Differences in surgical education also explain much of the global variation in OPCAB adoption, with countries such as Brazil and India incorporating beating-heart techniques more extensively into residency and fellowship training than many centers in North America and Europe[29].

CLINICAL OUTCOMES: EVIDENCE FROM RANDOMIZED AND OBSERVATIONAL STUDIES

The comparative evidence between OPCAB and conventional ONCAB is derived from randomized controlled trials (RCTs) and large contemporary observational studies. Landmark RCTs, including ROOBY, CORONARY, and GOPCABE, provide the highest level of evidence, while modern registries increasingly use propensity score matching, weighting, and stratification to reduce treatment-selection bias. Together, these complementary data provide the foundation for current understanding of OPCAB outcomes.

Overall, the major randomized trials demonstrated no significant differences in early mortality between OPCAB and ONCAB. Thirty-day mortality was similar in ROOBY (1.6% *vs.* 1.2%), CORONARY (2.5% *vs.* 2.5%), and GOPCABE (2.6% *vs.* 2.8%), while long-term follow-up showed comparable rates of death, myocardial infarction, stroke, and dialysis-requiring renal failure.

Despite these equivalent survival outcomes, OPCAB consistently reduced several perioperative complications, including blood transfusion, atrial fibrillation, reoperation for bleeding, acute kidney injury, and respiratory complications during the early postoperative period. Although the reduction in acute kidney injury has not translated into improved long-term renal function, these findings support the physiological benefits of avoiding CPB.

One of the principal concerns regarding OPCAB has been the potential for less complete revascularization, reflected by a modest reduction in the number of distal anastomoses reported in some randomized trials. Nevertheless, long-term survival and major adverse cardiovascular events remain comparable to ONCAB when OPCAB is performed by experienced surgeons capable of achieving complete revascularization. Likewise, the absence of a consistent reduction in stroke in some randomized trials may partly reflect crossover of patients with severely calcified aortas, thereby diminishing the potential benefit of an anaortic or no-touch strategy[30-37].

GRAFT PATENCY AND COMPLETENESS OF REVASCULARIZATION

Long-term graft patency and completeness of revascularization have remained among the most debated aspects of OPCAB. Early randomized trials, particularly the ROOBY trial, reported fewer distal anastomoses, lower graft patency, and higher rates of incomplete revascularization compared with ONCAB. These findings raised concerns regarding the ability of OPCAB to achieve durable multivessel revascularisation and were widely interpreted as evidence of inherent limitations of the beating-heart technique.

Subsequent analyses, however, have demonstrated that these early results were influenced largely by surgeon experience, institutional case volume, and the learning curve associated with beating-heart surgery rather than by the technique itself. During the evolution of OPCAB, significant technical advances, including improved cardiac positioning devices, coronary stabilizers, intracoronary shunts, blower–mister systems, and the posterior pericardial traction suture (Lima stitch) have largely overcome the technical challenges of constructing precise distal anastomoses while maintaining haemodynamic stability. These developments have enabled experienced surgeons to perform complete multivessel myocardial revascularization with reproducible technical quality.

Evidence from high-volume centres with established OPCAB programmes, supported by contemporary observational studies, propensity-matched analyses, and meta-analyses, has consistently demonstrated rates of complete revascularization, graft patency, long-term survival, and freedom from major adverse cardiovascular events comparable to those achieved with conventional ONCAB. In contrast, centres performing relatively few off-pump procedures continue to report higher conversion rates, less complete revascularization, and inferior graft patency, highlighting the critical influence of surgical expertise and institutional experience. These observations have fundamentally changed the interpretation of the available evidence. The debate has shifted from questioning whether OPCAB can achieve complete and durable revascularization to recognising that outcomes are determined primarily by surgeon proficiency, technical standardisation, and appropriate patient selection. Current clinical guidelines therefore emphasise that the objective of coronary surgery is complete and durable myocardial revascularization irrespective of the operative technique employed. When performed by experienced surgeons capable of achieving this standard, incomplete revascularization should no longer be regarded as an inherent limitation of OPCAB but rather as a potentially avoidable consequence of inadequate experience, insufficient training, or inappropriate patient selection[38-41].

ORGAN-SPECIFIC OUTCOMES OF OFF-PUMP CORONARY ARTERY BYPASS GRAFTING

Avoiding CPB is one of the principal physiological advantages of OPCAB. CPB activates complement pathways, leukocytes, endothelial cells, and inflammatory cytokines, contributing to systemic inflammatory response syndrome and postoperative organ dysfunction. Randomized and observational studies have consistently demonstrated that OPCAB attenuates this inflammatory response, with reduced release of pro-inflammatory cytokines such as interleukin-6 and interleukin-8, lower myocardial injury markers, and decreased oxidative stress. Although these biological benefits do not consistently translate into improved long-term clinical outcomes, they provide the mechanistic basis for many of the perioperative advantages observed with OPCAB, particularly in high-risk patients[42].

Neurological protection remains one of the most important, proposed advantages of OPCAB. By avoiding CPB and, more importantly, minimizing or eliminating manipulation of the ascending aorta, OPCAB has the potential to reduce cerebral embolization and perioperative stroke[30,35,43,44].

Observational studies and meta-analyses, particularly those evaluating anaortic ("no-touch") techniques, consistently demonstrate lower rates of postoperative stroke compared with ONCAB. In contrast, the major randomized trials, including ROOBY, CORONARY, and GOPCABE, reported similar stroke rates between OPCAB and ONCAB. This discrepancy likely reflects the relatively low baseline stroke risk of trial participants and the fact that most patients still underwent some degree of aortic manipulation, thereby limiting the potential neurological advantage of OPCAB.

Evidence regarding postoperative cognitive function is less consistent. Although several studies suggest a reduction in early neurocognitive dysfunction, long-term follow-up has generally failed to demonstrate sustained differences between the two techniques. Current evidence therefore indicates that the greatest neurological benefit is achieved when OPCAB is combined with an anaortic revascularization strategy in patients with extensive aortic atherosclerosis or other risk factors for cerebrovascular events[45,46].

Reduced perioperative blood transfusion is one of the most consistent clinical advantages of OPCAB. Avoidance of CPB minimizes hemodilution, platelet dysfunction, and coagulation abnormalities, thereby preserving more physiological hemostasis. Consequently, randomized trials and meta-analyses consistently demonstrate reduced platelet and fresh frozen plasma transfusion requirements, while reductions in red blood cell transfusion are most evident in experienced centres using contemporary blood conservation protocols.

Transfusion requirements remain influenced by patient characteristics, including preoperative anemia, chronic kidney disease, urgent surgery, recent P2Y12 inhibitor therapy, thrombocytopenia, and hypoalbuminemia. Equally important are meticulous surgical haemostasis, optimized anesthetic management, point-of-care coagulation monitoring, and comprehensive patient blood management programmes.

When combined with appropriate patient selection and experienced surgical teams, OPCAB substantially reduces exposure to allogeneic blood products, contributing to shorter intensive care and hospital stays, lower healthcare costs, and enhanced postoperative recovery[30,45,46].

PATIENT SELECTION

Appropriate patient selection remains fundamental to successful OPCAB. While outcomes in lower-risk patients are generally comparable to those of ONCAB, the greatest benefits appear to be confined to carefully selected high-risk populations. Candidate selection should consider coronary anatomy, ventricular function, comorbidities, anticipated technical complexity, and, importantly, surgical and institutional experience. Variability in these factors has contributed substantially to the heterogeneity of published outcomes.

Current evidence suggests that patients most likely to benefit from OPCAB include the elderly, particularly those over 75 years of age; patients with severe ascending aortic calcification or a porcelain aorta; individuals with chronic kidney disease or impaired renal reserve; patients with reduced left ventricular function; and those with multiple comorbidities, including diabetes mellitus, peripheral arterial disease, or frailty. In these populations, avoiding CPB and minimizing aortic manipulation may reduce perioperative organ injury while maintaining equivalent long-term outcomes. Standardized selection criteria, combined with appropriate surgical expertise, are essential to maximize the benefits of OPCAB[30,34,35,46-48].

ELDERLY PATIENTS

Elderly patients derive some of the greatest potential benefit from OPCAB because of their reduced physiological reserve and high prevalence of frailty, cerebrovascular disease, chronic kidney disease, and other age-related comorbidities. Avoiding CPB and minimizing aortic manipulation may reduce perioperative organ injury in this vulnerable population.

Randomized trials, observational studies, and meta-analyses have demonstrated lower rates of perioperative complications,

including stroke, acute kidney injury, blood transfusion, and postoperative atrial fibrillation, in carefully selected elderly patients undergoing OPCAB. Additional benefits include shorter intensive care and hospital stays and reduced resource utilization. In octogenarians, OPCAB achieves operative mortality and long-term survival comparable to ONCAB when complete revascularization is performed by experienced surgical teams.

Overall, the available evidence supports OPCAB as an important revascularization strategy for selected elderly patients, with outcomes determined more by completeness of revascularization, ventricular function, conduit selection, and comorbidity burden than by chronological age alone[34,35,45].

RENAL DYSFUNCTION

Renal protection has been one of the main proposed advantages of OPCAB because CPB contributes to acute kidney injury through hemodilution, systemic inflammation, ischemia–reperfusion injury, and microembolic phenomena. While the major randomized trials reported similar rates of postoperative renal dysfunction after OPCAB and ONCAB, large observational studies and meta-analyses have demonstrated lower rates of acute kidney injury, particularly among patients with pre-existing chronic kidney disease.

Current evidence suggests that the renal benefits of OPCAB are greater in patients with impaired baseline renal function or limited renal reserve. Although a consistent reduction in dialysis requirement or long-term renal outcomes has not been demonstrated, OPCAB represents a reasonable revascularization strategy for carefully selected patients with chronic kidney disease when performed by experienced surgical teams[31,34,35,49].

CHRONIC OBSTRUCTIVE PULMONARY DISEASE

Pulmonary dysfunction is a frequent complication after coronary artery bypass surgery and contributes to prolonged mechanical ventilation, longer intensive care stays, and increased postoperative morbidity. By avoiding CPB, OPCAB attenuates pulmonary inflammatory injury and preserves early respiratory function better. Several studies have demonstrated improved pulmonary mechanics, less impairment of gas exchange, and shorter ventilation times, with the greatest benefit observed in elderly patients and those with chronic obstructive pulmonary disease[35,39,45,46].

DIABETES MELLITUS

Patients with diabetes mellitus frequently present with diffuse multivessel coronary disease, renal dysfunction, cerebrovascular disease, impaired wound healing, and an increased risk of postoperative infection. These characteristics make strategies that minimize perioperative organ injury particularly attractive.

Although randomized trials have not demonstrated a consistent survival advantage for OPCAB, observational studies suggest reductions in perioperative complications, including acute kidney injury, stroke, and pulmonary complications. However, these potential benefits must be balanced against the technical challenge of achieving complete revascularization in patients with diffuse coronary disease. Consequently, optimal outcomes depend on meticulous operative technique, complete myocardial revascularization, strict perioperative glycaemic control, careful conduit selection, and meticulous sternal management. When these principles are applied, OPCAB provides a safe and effective revascularization strategy for appropriately selected diabetic patients[30,39,50,51].

LEFT VENTRICULAR DYSFUNCTION

Patients with left ventricular dysfunction represent one of the most challenging groups undergoing CABG. The rationale for OPCAB is that avoiding CPB and global myocardial ischemia may reduce additional myocardial injury and facilitate postoperative recovery. However, displacement of a dilated, poorly functioning heart may itself produce significant hemodynamic instability, making these procedures technically demanding.

Current evidence indicates that OPCAB can be performed safely in selected patients with reduced left ventricular ejection fraction, particularly in experienced centres. Although randomized trials have not demonstrated a consistent survival advantage over conventional CABG, carefully selected patients may benefit from reduced perioperative morbidity while achieving equivalent long-term outcomes[31,34,35].

COST-EFFECTIVENESS AND RESOURCE UTILIZATION

From a health economics perspective, OPCAB has the potential to reduce resource utilization by decreasing perioperative blood transfusions, shortening mechanical ventilation time, reducing intensive care unit and hospital length of stay, and lowering the incidence of complications associated with CPB. Early randomized trials demonstrated lower hospital costs with OPCAB, whereas more recent meta-analyses indicate that these economic advantages are closely linked to surgeon and institutional experience. Consequently, OPCAB appears to be most cost-effective when performed in high-volume centers capable of achieving complete revascularization with low conversion rates and excellent clinical outcomes[30,34,35,39,46].

WORLDWIDE ADOPTION OF OFF-PUMP CORONARY ARTERY BYPASS GRAFTING

Despite more than three decades of clinical experience and extensive scientific evidence, the global adoption of OPCAB remains highly variable. Unlike many surgical innovations that become universally adopted, OPCAB has followed distinct regional pathways shaped by surgical culture, training, institutional expertise, healthcare systems, and interpretation of the clinical evidence.

Asia has consistently reported the highest rates of OPCAB utilization, particularly in Japan, South Korea, India, and China, where many high-volume centres perform most coronary bypass procedures without CPB. This success reflects structured training programmes, institutional commitment, dedicated multidisciplinary teams, and continuous refinement of beating-heart techniques, resulting in excellent clinical outcomes and reproducible complete myocardial revascularization.

In North America, OPCAB expanded rapidly during the late 1990s and early 2000s but declined following publication of major randomized trials, particularly ROOBY, which raised concerns regarding graft patency and completeness of revascularization. Europe experienced a similar trend, with OPCAB now concentrated in specialised centres, while ONCAB remains the predominant approach. In both regions, OPCAB is used mainly in selected

high-risk patients, particularly those with severe ascending aortic calcification or significant comorbidity.

Latin America occupies a unique place in the history of OPCAB. The pioneering work of Enio Buffolo, in Brazil, and Federico Benetti, in Argentina, established the feasibility of routine beating-heart coronary surgery. Brazil continues to maintain several internationally recognised OPCAB centres, although adoption across Latin America remains heterogeneous.

Much of this geographical variation reflects differences in training, procedural volume, and institutional commitment. Economic considerations provide a further incentive for experienced programmes. These advantages, however, depend on maintaining procedural efficiency and are diminished in low-volume centres when conversion to CPB or incomplete revascularization occurs[31,35,34,45,48,52,53].

CHALLENGES LIMITING OFF-PUMP CORONARY ARTERY BYPASS GRAFTING ADOPTION

Despite more than three decades of clinical experience, OPCAB has not achieved universal adoption. The reasons are multifactorial and include the technical complexity of the procedure, variability in surgical training and institutional experience, differing interpretations of the clinical evidence, and disparities in healthcare resources. Consequently, OPCAB has become established as a highly specialized technique whose success depends on both surgical expertise and institutional commitment[30,46,48].

The principal barrier remains the steep learning curve associated with beating-heart surgery. Unlike conventional ONCAB, OPCAB requires precise coronary anastomoses on a moving heart while maintaining myocardial perfusion and hemodynamic stability. Mastery of cardiac positioning, exposure of the lateral and posterior coronary territories, and close coordination with the anaesthesia team require structured training, progressive skill acquisition, and sustained procedural volume. As a result, surgeon and centre experience remain among the strongest predictors of successful outcomes[37,54].

A further challenge is the declining exposure of trainees to OPCAB. Following publication of the major randomized trials, many centres substantially reduced their use of beating-heart surgery, limiting opportunities for trainees to develop proficiency. This has created a self-perpetuating cycle in which reduced experience leads to lower utilization, further diminishing training opportunities and threatening the preservation of specialized skills[48,52].

Successful implementation also depends on institutional infrastructure. Dedicated multidisciplinary teams, experienced cardiac anaesthesiologists, specialized nursing staff, appropriate stabilization technology, and sufficient procedural volume are essential to achieve consistent results. Without these elements, the potential advantages of OPCAB may be offset by increased conversion rates or incomplete revascularization[48,52,55,56].

Looking ahead, broader adoption of OPCAB will require continued investment in structured education, simulation-based training, technological innovation, and multidisciplinary collaboration. Advances in minimally invasive and robotic surgery, hybrid coronary revascularization, improved stabilization systems, high-fidelity simulation, and artificial intelligence–assisted surgical planning are likely to facilitate wider dissemination while maintaining procedural quality. Rather than replacing conventional CABG, OPCAB should be regarded as a complementary revascularization strategy that provides particular benefit for appropriately selected patients when performed by experienced surgical teams[30,37,41,48].

CURRENT EVIDENCE, GUIDELINE RECOMMENDATIONS, AND FUTURE PERSPECTIVES

More than three decades after its clinical introduction, OPCAB has evolved from an innovative alternative into a mature, evidence-based strategy for myocardial revascularization. Contemporary evidence demonstrates that, when performed by appropriately trained surgeons, OPCAB provides early and long-term clinical outcomes comparable to ONCAB, while offering advantages in selected high-risk patients.

These findings are reflected in current international guidelines. The 2021 American College of Cardiology/American Heart Association/Society for Cardiovascular Angiography and Interventions Guideline for Coronary Artery Revascularization and contemporary European recommendations advocate a patient-centred approach in which the choice of operative technique is determined by coronary anatomy, comorbidities, operative risk, and, importantly, the expertise of the surgeon and institution. Rather than viewing OPCAB and ONCAB as competing procedures, the guidelines recognise them as complementary techniques within the modern coronary surgeon's armamentarium. Both emphasise multidisciplinary heart team decision-making and support OPCAB when avoidance of CPB or aortic manipulation is expected to confer meaningful clinical benefit. Routine use of OPCAB for every patient is not recommended; instead, the emphasis is on selecting the right operation for the right patient[33-35,41,43,52-54,57].

This philosophy reflects a broader evolution in cardiac surgery toward precision medicine and individualized revascularization. The central question is no longer whether OPCAB is universally superior to ONCAB, but which patients are most likely to benefit from each approach. Success depends not on whether the heart is beating or arrested, but on achieving safe, complete, and durable myocardial revascularization tailored to the patient's anatomical complexity, physiological reserve, and associated comorbidities.

The continued success of OPCAB will depend largely on preserving and expanding surgical expertise. Because beating-heart coronary surgery requires advanced technical skills, maintaining proficiency through structured education is essential. Competency-based curricula, high-fidelity simulation, objective assessment of technical performance, dedicated fellowships, formal credentialing, and mentorship by experienced surgeons should become integral components of cardiac surgical training. Equally important is the concentration of complex OPCAB practice within centres that maintain sufficient procedural volume to preserve expertise, support multidisciplinary teams, and provide optimal patient outcomes.

Technological innovation is also likely to reshape the future of beating-heart surgery. Improvements in cardiac stabilization and exposure have already transformed the reproducibility of OPCAB, and further advances are expected through robotic-assisted surgery, minimally invasive coronary bypass, hybrid coronary revascularization, enhanced intraoperative imaging, three-dimensional visualization, augmented and virtual reality, and artificial intelligence-assisted planning and decision support. These technologies have the potential to improve operative precision, reduce technical variability, facilitate surgical training, and expand

access to complex coronary revascularization while preserving the principles of complete and durable grafting.

Future research should likewise evolve beyond simply comparing OPCAB with ONCAB. The major clinical questions have shifted toward identifying the patients who derive the greatest benefit from each strategy and determining how evolving technologies can be integrated into routine practice. Priorities include refining risk stratification and patient selection, evaluating anaortic and total arterial revascularization strategies, assessing long-term graft durability with contemporary imaging techniques, measuring neurocognitive recovery, functional status, and patient-reported outcomes, and defining the role of OPCAB within robotic and hybrid coronary revascularization programmes. Future clinical trials should also ensure standardized operative techniques and adequate surgeon experience, recognising that technical expertise remains one of the strongest determinants of clinical outcome. Viewed in this context, OPCAB should no longer be regarded as an alternative to conventional CABG, but as one of the established techniques available to the modern coronary surgeon. Its future lies not in replacing ONCAB but in complementing it within an increasingly personalized approach to coronary revascularization, where operative strategy is tailored to each patient's anatomy, risk profile, and clinical needs. As surgical technology, education, and perioperative care continue to advance, the distinction between off-pump and on-pump surgery will become less important than the consistent delivery of safe, durable, and patient-specific myocardial revascularization[37,48,54,58,59].

Data Availability

The authors declare that the data supporting the findings of this study are available within the article.

Artificial Intelligence Usage

The authors declare use of Chat GPT - CoPilot for grammar corrections. The content produced by the artificial intelligence tool was revised and edited by the authors as necessary, and they take full responsibility for the content to be published.

Potential Conflict of Interest

The authors declare that there is no conflict of interest in this study.

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Authors' Roles & Responsibilities

RCL	Substantial contributions to the conception or design of the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published
TAS	Substantial contributions to the conception or design of the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published
GDA	Substantial contributions to the conception or design of the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published
EB	Substantial contributions to the conception or design of the work; drafting the work or revising it critically for important intellectual content; final approval of the version to be published

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