ISSN: 2753-7919
British Journal of Healthcare and Medical Research; Vol. 13 No. 01 (2026) (91-113)
https://doi.org/10.14738/bjhr.1301.19803

SWOT Analysis of Off-pump Coronary Artery Bypass Grafting

Amna Zafar & Shahzad G. Raja

1. Department of Cardiac Surgery, Harefield Hospital, London, United Kingdom

Abstract: Off pump coronary artery bypass grafting (OPCAB) has undergone significant evolution since its introduction as an alternative to conventional on pump CABG. By avoiding cardiopulmonary bypass (CPB) and minimizing aortic manipulation, OPCAB aims to reduce perioperative morbidity, neurological complications, and systemic inflammatory responses. Despite these theoretical advantages, its adoption has varied widely across institutions due to concerns regarding graft patency, completeness of revascularization, and operator dependency. This state of the art review provides a comprehensive SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis of OPCAB, integrating evidence from randomized trials, meta analyses, and large observational studies. The strengths of OPCAB include reduced stroke risk, lower perioperative morbidity in high risk populations, decreased bleeding and transfusion requirements, and compatibility with anaortic total arterial revascularization. Weaknesses include technical complexity, variability in surgeon experience, concerns regarding long term graft patency, and inconsistent evidence from randomized trials. Emerging opportunities include the expansion of anaortic no touch techniques, integration with minimally invasive and robotic platforms, advances in intraoperative imaging, and the potential for subspecialty training to standardize outcomes. Threats include declining surgeon experience, competition from percutaneous coronary intervention and hybrid revascularization strategies, persistent skepticism regarding patency and completeness of revascularization, and economic or technological barriers to widespread adoption. Through a structured SWOT framework, this review synthesizes contemporary evidence to clarify OPCAB's current role and future trajectory in coronary surgery. The analysis highlights the importance of surgeon expertise, institutional commitment, and technological integration in optimizing outcomes. OPCAB remains a valuable strategy for selected patients, particularly those at elevated risk for neurological complications or adverse effects of CPB.

Keywords: Anaortic coronary artery surgery, cardiopulmonary bypass, coronary artery bypass, off-pump coronary artery bypass, SWOT analysis.

INTRODUCTION

Off-pump coronary artery bypass grafting (OPCAB) was developed to mitigate the physiological burden associated with cardiopulmonary bypass (CPB), including systemic inflammation, coagulopathy, neurocognitive dysfunction, and end-organ injury [1]. Early enthusiasm for OPCAB was driven by the potential to reduce perioperative morbidity, particularly in high-risk patients with significant comorbidities [2]. Over the past three decades, the technique has evolved substantially, supported by advances in stabilizers, exposure devices, anesthetic management, and conduit strategies [3]. Despite these developments, OPCAB remains a subject of ongoing debate, with adoption varying widely across institutions and regions.

The evidence base for OPCAB is extensive but heterogeneous. Randomized controlled trials (RCTs) have produced mixed results, often influenced by surgeon experience, patient selection, and institutional expertise [4]. Meta-analyses of RCTs have raised concerns regarding graft patency and long-term mortality [5,6], whereas large observational studies and registry data frequently demonstrate reduced perioperative complications and comparable long-term outcomes [7-9]. This divergence underscores the operator-dependent nature of OPCAB and highlights the importance of technical proficiency in achieving optimal results. Furthermore, the emergence of anaortic, no-touch techniques has renewed interest in OPCAB as a strategy to minimize neurological complications, particularly stroke [10].

In parallel, the landscape of coronary revascularization has evolved with the rise of minimally invasive and robotic CABG, hybrid coronary revascularization (HCR), and increasingly sophisticated percutaneous coronary intervention (PCI) technologies [11]. These developments have reshaped the competitive environment in which OPCAB operates. At the same time, enhanced recovery protocols, intraoperative imaging modalities, and total arterial grafting strategies have expanded the potential applications of OPCAB, particularly in centers with specialized expertise.

Given this complex and evolving context, a structured SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides a valuable framework for assessing OPCAB’s current role and future trajectory. By synthesizing contemporary evidence across multiple domains, this review aims to clarify the clinical, technical, and strategic considerations that influence OPCAB adoption and outcomes. The goal is to provide clinicians, researchers, and policymakers with a comprehensive, evidence-based assessment of OPCAB’s strengths and limitations, as well as the opportunities and challenges that will shape its future in coronary surgery.

STRENGTHS

OPCAB offers several well-documented advantages over conventional on-pump CABG, particularly in reducing perioperative morbidity and neurological complications [1]. These strengths stem primarily from the avoidance of CPB and reduced aortic manipulation, both of which contribute to systemic inflammation, embolic risk, and end-organ dysfunction [12]. Over the past three decades, refinements in stabilizers, exposure techniques, anesthetic management, and conduit strategies have further enhanced the safety and reproducibility of OPCAB in experienced centers [3]. As a result, OPCAB has emerged as a compelling option for selected patient populations, especially those at elevated risk for CPB-related complications.

A major strength of OPCAB is its ability to minimize neurological injury. Stroke remains one of the most feared complications of CABG, with profound implications for mortality, disability, and quality of life [13]. By eliminating aortic cannulation and cross-clamping, OPCAB significantly reduces the risk of embolic events, particularly when performed using anaortic, no-touch techniques. This benefit is consistently demonstrated across meta-analyses and large observational cohorts, making OPCAB a preferred strategy in patients with a heavily calcified aorta or prior cerebrovascular disease [14].

OPCAB also confers advantages in high-risk populations, including those with chronic obstructive pulmonary disease (COPD) [15], chronic kidney disease (CKD) [16], left ventricular dysfunction [7], and advanced age [8]. These patients often experience exaggerated inflammatory responses and hemodynamic instability during CPB, making OPCAB an attractive alternative. Evidence suggests that OPCAB reduces ventilation time, renal injury, and early mortality in these groups, although long-term outcomes depend heavily on surgical expertise and completeness of revascularization.

Finally, OPCAB facilitates the use of anaortic total arterial grafting, a strategy associated with superior long-term patency and reduced stroke risk. Composite grafting techniques, including T- and Y-configurations, are particularly well suited to the beating-heart environment and allow surgeons to achieve complete revascularization without manipulating the ascending aorta [17]. This synergy between OPCAB and total arterial revascularization represents a major strength that aligns with contemporary trends toward minimizing aortic manipulation and maximizing graft durability (Figure 1).

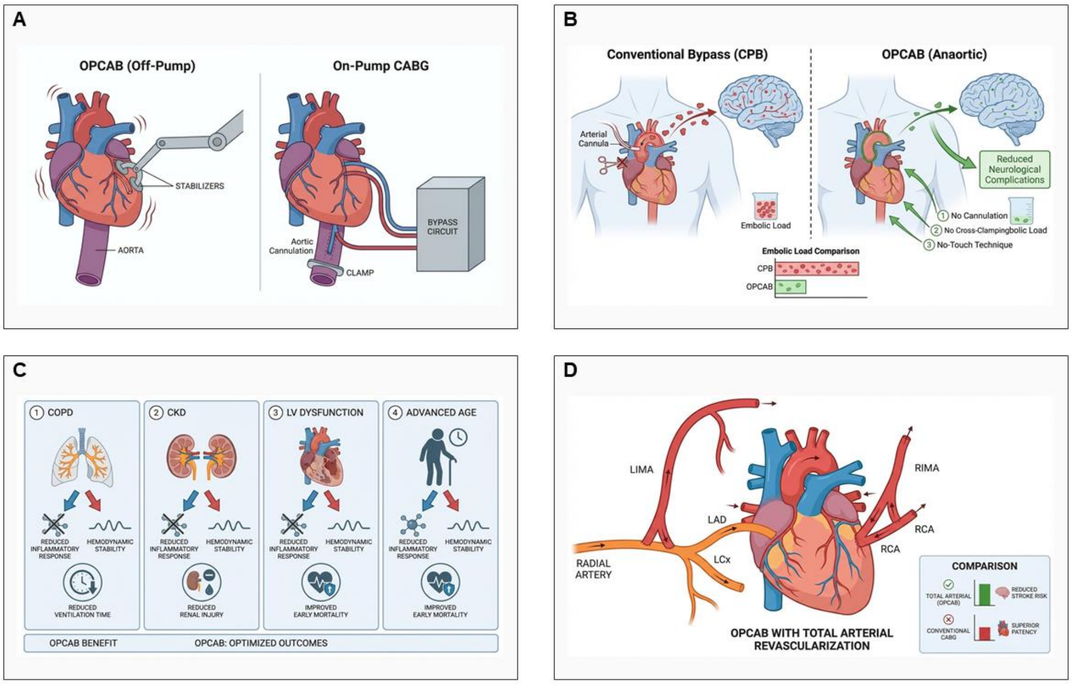

Figure 1. OPCAB Advantages: Mechanisms, Benefits, and Clinical Applications

(A) OPCAB eliminates CPB and aortic manipulation compared to on-pump CABG. This panel illustrates the fundamental technical differences between off-pump and on-pump coronary artery bypass grafting procedures.

(B) OPCAB reduces embolic stroke risk via anaortic, no-touch techniques. Neurological protection mechanisms are demonstrated through avoidance of aortic manipulation and cardiopulmonary bypass-related embolic events.

(C) OPCAB improves outcomes in COPD, CKD, LV dysfunction, and advanced age. High-risk patient populations that particularly benefit from off-pump techniques are shown with associated clinical outcome improvements.

(D) Total arterial composite grafting with OPCAB maximizes patency and safety. Optimal revascularization strategies combining total arterial grafts with off-pump technique for enhanced long-term outcomes are illustrated.

Reduced Neurological Complications

Neurological injury remains one of the most devastating complications of CABG, with postoperative stroke occurring in 1–3% of patients undergoing conventional on-pump surgery [18]. The pathophysiology is multifactorial, involving embolization from aortic manipulation, hypoperfusion during CPB, and systemic inflammatory responses. OPCAB directly addresses these mechanisms by avoiding CPB and, in many cases, eliminating aortic manipulation altogether. This reduction in embolic load is particularly important in patients with atherosclerotic or “porcelain” aortas, where even minimal manipulation can dislodge debris [19].

A landmark network meta-analysis involving more than 37,000 patients demonstrated that anaortic OPCAB was associated with the lowest postoperative stroke risk among all revascularization strategies, outperforming both conventional on-pump CABG and partial-clamp OPCAB techniques [20]. These findings were reinforced by single-center series showing significantly reduced early stroke rates with anaortic approaches, even in high-risk cohorts [21]. Importantly, the stroke-sparing effect of OPCAB appears consistent across diverse patient populations, including the elderly and those with prior cerebrovascular events.

Beyond clinically overt stroke, OPCAB may also reduce subclinical neurological injury. Studies using neurocognitive testing and imaging modalities such as diffusion-weighted MRI have shown lower rates of microembolic lesions in patients undergoing OPCAB compared with on-pump CABG. Although the long-term cognitive implications remain debated, the reduction in embolic burden is biologically plausible and aligns with the observed decrease in clinical stroke [22].

The neurological benefits of OPCAB are further amplified when combined with total arterial, anaortic grafting strategies. Composite grafts constructed from the internal thoracic and radial arteries allow surgeons to avoid the ascending aorta entirely, thereby eliminating the primary source of embolic debris [17]. This synergy between OPCAB and anaortic grafting represents one of the most compelling strengths of the technique and has driven renewed interest in beating-heart revascularization in the modern era.

Lower Perioperative Morbidity in High-Risk Patients

High-risk patients—such as those with chronic obstructive pulmonary disease (COPD), chronic kidney disease (CKD), diabetes, advanced age, or left ventricular dysfunction—are particularly vulnerable to the physiological stresses of CPB. OPCAB offers a less invasive alternative that mitigates many of these risks. In patients with COPD, for example, OPCAB has been associated with reduced ventilation time, lower rates of pulmonary complications, and shorter intensive care unit (ICU) stays compared with on-pump CABG [15]. These benefits are attributed to the avoidance of CPB-induced pulmonary inflammation and fluid shifts, which can exacerbate respiratory dysfunction.

Patients with CKD also derive meaningful benefit from OPCAB. Meta-analyses suggest that OPCAB reduces short-term mortality and postoperative renal injury in this population [23]. CPB is known to trigger renal hypoperfusion, hemolysis, and inflammatory cascades that can precipitate acute kidney injury. By maintaining more stable hemodynamics and avoiding non-pulsatile flow, OPCAB reduces renal stress and may improve early outcomes, although long-term renal benefits remain uncertain.

In patients with left ventricular dysfunction, OPCAB has demonstrated reductions in early mortality, stroke, myocardial infarction, and renal failure compared with on-pump CABG [24]. These findings are particularly relevant given the hemodynamic fragility of this group. OPCAB allows for tailored stabilization and positioning strategies that minimize cardiac manipulation and maintain adequate perfusion pressures throughout the procedure.

Elderly patients also benefit from OPCAB's reduced physiological burden. Age-related frailty, vascular stiffness, and comorbidities increase susceptibility to CPB-related complications. Observational studies consistently show lower rates of delirium, renal injury, and shortened ventilation in elderly patients undergoing OPCAB [25]. Although long-term survival depends on comorbidity burden and completeness of revascularization, the perioperative advantages of OPCAB in this population are well established.

Reduced Bleeding, Transfusion, and Inflammatory Response

Avoidance of CPB confers significant hematologic and inflammatory advantages. CPB is associated with hemodilution, platelet dysfunction, activation of coagulation pathways, and systemic inflammatory response syndrome (SIRS). These effects contribute to increased bleeding, transfusion requirements, and postoperative complications. OPCAB minimizes these physiological disturbances, resulting in more stable perioperative hemostasis [26].

Multiple studies have demonstrated lower transfusion rates in OPCAB compared with on-pump CABG [27,28]. Reduced hemodilution and preservation of platelet function contribute to this benefit. Lower transfusion requirements are clinically meaningful, as transfusion is independently associated with increased infection, renal injury, and mortality. By reducing the need for blood products, OPCAB may indirectly improve postoperative outcomes [28].

OPCAB also attenuates the systemic inflammatory response. CPB triggers complement activation, cytokine release, and endothelial dysfunction, all of which contribute to postoperative organ injury. Studies have shown lower levels of inflammatory markers such as IL-6 and CRP in OPCAB patients, correlating with reduced pulmonary dysfunction, shorter ventilation times, and faster recovery [29,30]. These benefits are particularly relevant in patients with pre-existing inflammatory conditions or impaired physiological reserve.

Reduced bleeding and inflammation also translate into shorter ICU and hospital stays [27-30]. Enhanced recovery protocols, which emphasize early mobilization and reduced opioid use, are more easily implemented in OPCAB patients due to their more stable postoperative course. This synergy between OPCAB and enhanced recovery pathways represents an important strength that aligns with modern perioperative care principles.

Compatibility with Anaortic Total Arterial Revascularization

One of OPCAB’s most significant strengths is its compatibility with anaortic total arterial revascularization. By using composite grafts constructed from the internal thoracic and radial arteries, surgeons can achieve complete revascularization without manipulating the ascending aorta. This strategy not only reduces stroke risk but also enhances long-term graft durability, as arterial conduits have superior patency compared with saphenous vein grafts.

Composite T- and Y-grafts are particularly well suited to the beating-heart environment. These configurations allow multiple coronary targets to be reached from a single inflow source, reducing the need for aortic anastomoses. Hemodynamic studies demonstrate that composite arterial grafts maintain diastolic-dominant flow patterns that closely mimic native coronary physiology [31,32]. These favorable flow characteristics may contribute to improved long-term patency and reduced competitive flow.

Hybrid configurations combining no-touch saphenous vein grafts with left internal thoracic artery (LITA) inflow have also shown promising results. In a large cohort, competitive flow was infrequent, and one-year patency rates were high, particularly when SVGs were harvested with pedicle tissue [33]. These findings suggest that even vein grafts may perform better when integrated into anaortic composite constructs.

The synergy between OPCAB and total arterial grafting aligns with contemporary trends toward minimizing aortic manipulation and maximizing graft durability. As evidence continues to accumulate supporting the long-term benefits of arterial conduits, OPCAB's role as a platform for anaortic revascularization is likely to expand. This represents a major strategic strength that differentiates OPCAB from conventional on-pump CABG and positions it favorably within the evolving landscape of coronary surgery.

WEAKNESSES

Despite its advantages, OPCAB remains limited by several well-recognized weaknesses that have constrained its widespread adoption. These limitations stem largely from the technical demands of operating on a beating heart, variability in surgeon experience [34], and concerns regarding long-term graft durability [35]. Unlike on-pump CABG, which provides a motionless and bloodless field, OPCAB requires precise anastomotic construction under dynamic conditions. This increases the risk of technical errors, incomplete revascularization, and suboptimal graft geometry, particularly in less experienced hands. As a result, outcomes in OPCAB are more heterogeneous across institutions compared with conventional CABG (Figure 2).

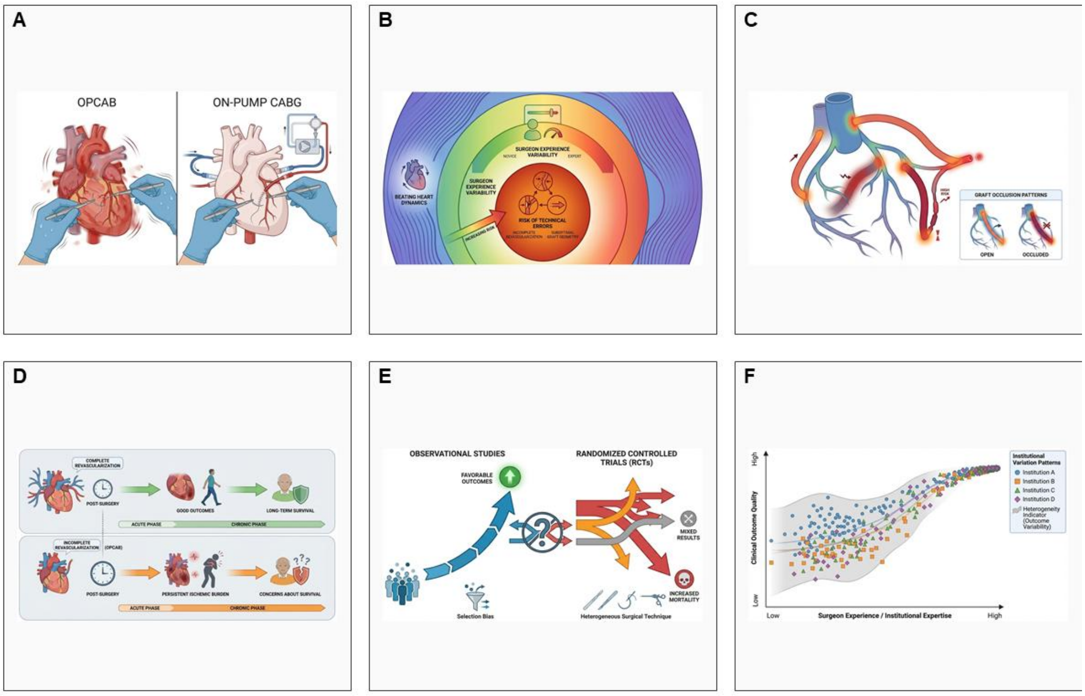

Figure 2. OPCAB Technical Limitations and Clinical Challenges

(A) OPCAB requires anastomosis on beating heart versus motionless on-pump field.
(B) Technical errors increase with inexperience and cardiac motion.
(C) Higher graft occlusion rates in saphenous vein and posterior vessel anastomoses.
(D) OPCAB patients receive fewer grafts, raising long-term ischemic burden concerns.
(E) Observational studies show favorable outcomes versus mixed RCT evidence.
(F) OPCAB outcomes highly dependent on surgeon experience and institutional expertise.

Another major weakness is the persistent concern regarding graft patency. Multiple randomized trials and meta-analyses have reported higher rates of graft occlusion with OPCAB, especially in saphenous vein grafts and anastomoses to small or posterior vessels [5,36]. These findings have fueled skepticism among surgeons and guideline committees, limiting OPCAB's acceptance as a standard approach. Although experienced centers report excellent patency rates, the variability in outcomes underscores the technique's operator dependency.

Completeness of revascularization is another area of concern. Several studies have shown that OPCAB patients receive fewer grafts on average than those undergoing on-pump CABG, raising questions about long-term ischemic burden and survival. While some of this difference reflects appropriate patient selection, incomplete revascularization remains a recognized limitation of OPCAB, particularly in multivessel or complex coronary disease [37].

Finally, the evidence base for OPCAB is complicated by inconsistent long-term results from randomized trials. While observational studies often show favorable outcomes, RCTs have produced mixed findings, with some suggesting increased long-term mortality. This discrepancy has contributed to ongoing controversy and has hindered the development of strong guideline recommendations in favor of OPCAB.

Operator Dependency and Technical Complexity

OPCAB is inherently more technically demanding than on-pump CABG. The surgeon must construct precise anastomoses on a beating heart while maintaining hemodynamic stability and adequate exposure. This requires mastery of stabilizers, positioners, and myocardial displacement techniques, as well as close coordination with anesthesia. As a result, OPCAB outcomes are highly sensitive to surgeon experience, with steep learning curves documented in multiple studies. Low-volume surgeons often struggle to achieve the same graft quality and completeness of revascularization as high-volume experts [38].

The ART trial and other multicenter RCTs highlighted the impact of surgeon experience on outcomes. In these trials, many participating surgeons performed relatively few OPCAB procedures annually, which likely contributed to neutral or unfavorable results [39]. In contrast, high-volume centers consistently report excellent outcomes, suggesting that OPCAB's weaknesses are not intrinsic to the technique but rather reflect variability in operator proficiency. This operator dependency remains a major barrier to broader adoption, as many institutions lack the case volume or training infrastructure to support consistent expertise.

Technical complexity also affects intraoperative decision-making. Challenging coronary targets—such as small, intramyocardial, or posterior vessels—may be more difficult to access on a beating heart. Hemodynamic instability during cardiac displacement can further limit the surgeon's ability to perform complete revascularization. These challenges contribute to the perception that OPCAB is less suitable for patients with diffuse or complex coronary disease, despite evidence that experienced surgeons can achieve excellent results even in these scenarios [40].

Finally, the technical demands of OPCAB extend beyond the surgeon. Successful beating-heart surgery requires a coordinated team, including anesthesiologists skilled in volume management and hemodynamic optimization, perfusionists prepared for emergent conversion, and nursing staff familiar with specialized equipment [40]. Institutions lacking this multidisciplinary expertise may experience inferior outcomes, reinforcing the operator-dependent nature of OPCAB.

Concerns Regarding Graft Patency

Graft patency remains one of the most frequently cited weaknesses of OPCAB. Multiple randomized trials and meta-analyses have reported higher rates of early and mid-term graft occlusion compared with on-pump CABG. A major meta-analysis of randomized evidence found that OPCAB was associated with increased graft failure (RR 1.31 overall), with particularly concerning results for saphenous vein grafts (RR 1.40) and even LITA-to-LAD anastomoses (RR 1.52) [5]. These findings have raised questions about the technical precision achievable on a beating heart.

Several mechanisms may contribute to reduced patency in OPCAB. Motion of the target vessel can impair visualization and needle control, increasing the risk of imperfect anastomotic geometry. Hemodynamic instability during cardiac displacement may compromise myocardial perfusion, leading to competitive flow or early graft thrombosis [40]. Additionally, incomplete exposure of posterior or lateral vessels may result in suboptimal graft placement or omission of important targets. These technical challenges are magnified in low-volume centers or among surgeons with limited OPCAB experience [40]. However, it is important to note that patency concerns are not universal. High-volume OPCAB centers consistently report patency rates comparable to on-pump CABG, particularly when arterial conduits and composite grafting strategies are used. This suggests that patency issues are largely operator-dependent rather than inherent to the technique. Nevertheless, the variability in outcomes across institutions has contributed to persistent skepticism and has limited guideline endorsement of OPCAB as a standard approach.

The perception of inferior patency has broader implications for OPCAB's reputation and adoption. Surgeons may be reluctant to perform OPCAB in younger patients or those with complex disease due to concerns about long-term durability. This creates a self-reinforcing cycle: reduced use leads to reduced experience, which in turn perpetuates inferior outcomes. Addressing patency concerns will require standardized training, routine use of intraoperative imaging, and greater emphasis on arterial and anaortic grafting strategies.

Incomplete Revascularization

Incomplete revascularization is another recognized weakness of OPCAB. Multiple studies have shown that patients undergoing OPCAB receive fewer grafts on average than those undergoing on-pump CABG [41]. While some of this difference reflects appropriate patient selection—such as avoiding grafting of small or poor-quality vessels—there is concern that technical limitations may prevent surgeons from achieving complete revascularization in multivessel disease. Incomplete revascularization has been associated with increased long-term mortality and major adverse cardiovascular events, making this a clinically significant issue [41].

The challenges of achieving complete revascularization during OPCAB stem from several factors. Exposure of lateral and posterior vessels often requires significant cardiac displacement, which can lead to hemodynamic instability. Surgeons may therefore avoid grafting certain targets to maintain patient safety. Additionally, the beating-heart environment can make it difficult to construct high-quality anastomoses on small or intramyocardial vessels. These limitations are particularly relevant in patients with diffuse coronary disease, left main stenosis, or complex multivessel involvement [40].

Evidence from randomized trials supports these concerns. Several RCTs have reported lower graft counts in OPCAB patients, and some have suggested that incomplete revascularization may contribute to increased long-term mortality [41]. Although observational studies from high-volume centers show that complete revascularization is achievable with OPCAB, the variability in outcomes across institutions remains a major weakness. This inconsistency has contributed to guideline recommendations that favor on-pump CABG for complex disease unless performed by highly experienced OPCAB surgeons.

Addressing incomplete revascularization will require improved training, better exposure techniques, and routine use of intraoperative imaging to verify graft quality. Composite grafting strategies and anaortic techniques may also facilitate more complete revascularization by reducing the need for aortic manipulation and enabling access to multiple targets from a single inflow source. Nevertheless, incomplete revascularization remains a significant limitation of OPCAB in many centers.

Limited Long-Term Randomized Evidence

The long-term evidence base for OPCAB is mixed, with randomized trials producing inconsistent results. While observational studies often show favorable outcomes, RCTs have raised concerns about long-term mortality and graft durability. For example, some meta-analyses of RCTs have reported increased long-term mortality with OPCAB (RR 1.09) [36], although other studies have found no significant difference at 10 years [42]. These conflicting findings have contributed to ongoing controversy and have hindered strong guideline endorsement of OPCAB.

Several factors contribute to the inconsistency in long-term evidence. Many RCTs enrolled surgeons with limited OPCAB experience, which likely biased results against the technique. Additionally, RCTs often excluded high-risk patients who might benefit most from OPCAB, limiting generalizability. Differences in conduit selection, intraoperative imaging, and postoperative management further complicate comparisons between studies. As a result, the true long-term benefits and risks of OPCAB remain incompletely defined.

The lack of robust long-term evidence has practical implications. Guideline committees have been cautious in recommending OPCAB, particularly for complex multivessel disease. Surgeons may be reluctant to adopt OPCAB due to concerns about long-term durability, especially in younger patients. This hesitancy contributes to declining OPCAB volumes, which in turn limits opportunities for training and skill development.

Future research will need to address these gaps through high-quality RCTs conducted in high-volume OPCAB centers with standardized protocols. Long-term follow-up, routine use of intraoperative imaging, and emphasis on arterial grafting will be essential to accurately assess OPCAB's long-term performance. Until such evidence is available, limited long-term data will remain a significant weakness of the technique.

OPPORTUNITIES

Despite the challenges associated with OPCAB, several emerging opportunities position it for renewed relevance in contemporary coronary surgery. Advances in surgical technology, imaging, conduit strategies, and perioperative care have expanded the potential applications of beating-heart revascularization. These developments not only address historical limitations of OPCAB but also align with broader trends toward minimally invasive, patient-centered, and precision-guided surgery. As a result, OPCAB is increasingly viewed not as a competing technique to on-pump CABG, but as a complementary strategy that can be tailored to specific patient populations and anatomical scenarios (Figure 3).

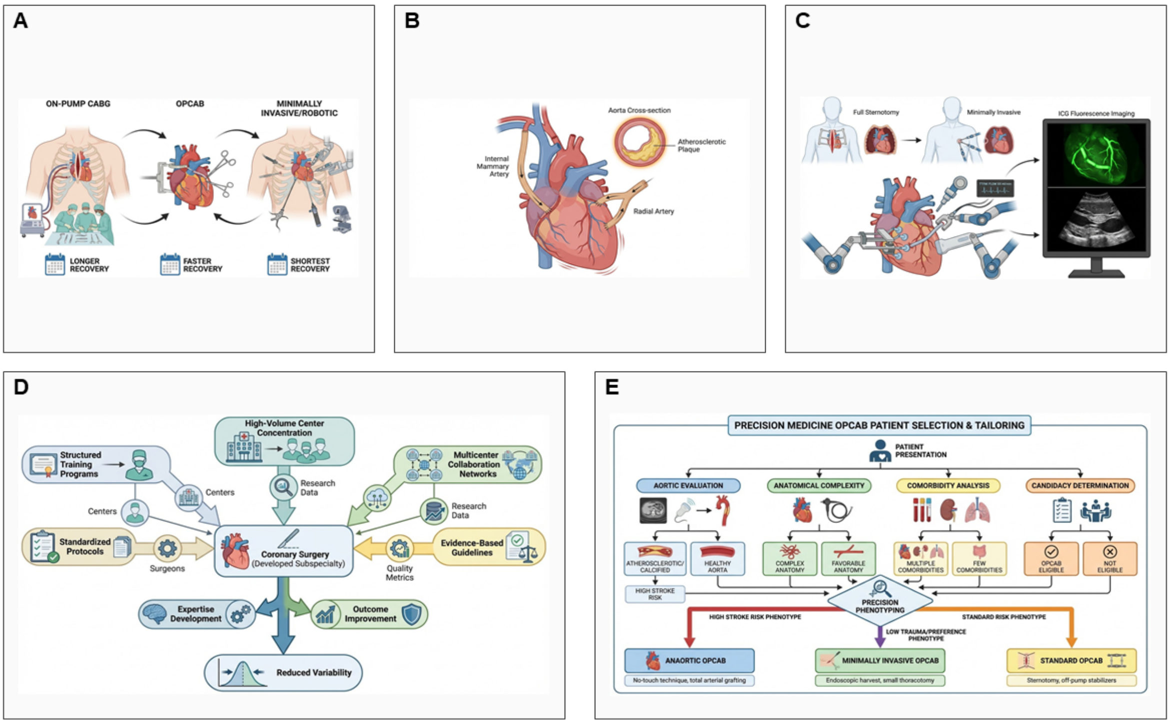

Figure 3. Emerging Opportunities in Off-Pump Coronary Artery Bypass (OPCAB) Surgery

(A) OPCAB positioned as complementary strategy across surgical spectrum.
(B) Anaortic no-touch technique with composite arterial grafting.
(C) Technological innovations: minimally invasive platforms and real-time imaging.
(D) Subspecialty development through training, protocols, and collaboration.
(E) Patient-centered precision selection and surgical strategy tailoring.

One of the most promising opportunities lies in the expansion of anaortic, no-touch techniques [17]. By eliminating aortic manipulation, these approaches significantly reduce the risk of stroke and embolic complications, making OPCAB particularly attractive for patients with atherosclerotic or calcified aortas. The integration of composite arterial grafting further enhances the feasibility of anaortic revascularization, offering a pathway to durable, stroke-sparing coronary surgery.

Technological innovations also present major opportunities for OPCAB. Minimally invasive and robotic platforms have matured substantially, enabling precise exposure and stabilization of coronary targets through small incisions. These approaches naturally complement OPCAB, as they avoid sternotomy and reduce surgical trauma. Similarly, advances in intraoperative imaging—such as transit-time flow measurement (TTFM), indocyanine green (ICG) fluorescence angiography, and high-resolution epicardial ultrasound—offer real-time verification of graft quality, addressing longstanding concerns about patency.

Finally, the growing recognition of coronary surgery as a subspecialty creates opportunities for structured training, standardized protocols, and multicenter collaboration. Concentrating expertise in high-volume centers can improve outcomes, reduce variability, and support the development of robust evidence. Together, these opportunities position OPCAB for a more prominent role in the future of coronary revascularization.

Expansion of Anaortic, No-Touch Techniques

Anaortic, no-touch techniques represent one of the most significant opportunities for OPCAB to expand its clinical impact. By avoiding any manipulation of the ascending aorta, these strategies virtually eliminate the risk of atheroembolic stroke—a complication that remains a major source of morbidity and mortality in conventional CABG. A large network meta-analysis involving more than 37,000 patients demonstrated that anaortic OPCAB was associated with the lowest postoperative stroke risk among all revascularization strategies [20]. This finding has been consistently replicated in single-center studies, which report significantly reduced early stroke rates with anaortic approaches [21].

The feasibility of anaortic OPCAB has been greatly enhanced by the development of composite arterial grafting techniques. T- and Y-configured grafts constructed from the internal thoracic and radial arteries allow surgeons to reach multiple coronary targets without requiring proximal anastomoses on the aorta. These configurations not only reduce stroke risk but also improve long-term graft durability, as arterial conduits have superior patency compared with saphenous vein grafts. Hemodynamic studies demonstrate that composite arterial grafts maintain diastolic-dominant flow patterns that closely mimic native coronary physiology, further supporting their use in anaortic strategies [31,32].

Anaortic OPCAB is particularly advantageous in patients with porcelain aorta, severe aortic calcification, or prior aortic surgery. In these high-risk populations, conventional on-pump CABG carries a substantial risk of embolic stroke due to aortic cannulation and cross-clamping. OPCAB offers a safer alternative that avoids these maneuvers entirely. As imaging modalities such as epiaortic ultrasound become more widely used, surgeons can better identify patients who would benefit from anaortic approaches.

The expansion of anaortic OPCAB also aligns with broader trends toward stroke prevention and minimally invasive surgery. As evidence continues to accumulate supporting the neurological benefits of no-touch techniques, guideline committees may increasingly endorse anaortic OPCAB for selected patients. This represents a major opportunity for OPCAB to differentiate itself from conventional CABG and to establish a clear niche in the management of complex coronary disease.

Integration with Minimally Invasive and Robotic CABG

Minimally invasive and robotic coronary artery bypass grafting (CABG) represent rapidly evolving fields that offer significant opportunities for OPCAB integration. Minimally invasive direct coronary artery bypass (MIDCAB) and totally endoscopic coronary artery bypass (TECAB) avoid sternotomy, reduce surgical trauma, and facilitate faster recovery. These approaches naturally complement OPCAB, as they rely on beating-heart techniques and avoid cardiopulmonary bypass. As robotic platforms have matured, exposure, stabilization, and anastomotic precision have improved, making robotic OPCAB increasingly feasible.

Evidence from high-volume centers demonstrates excellent outcomes with minimally invasive and robotic OPCAB. Mortality, stroke, and renal failure rates are consistently below 1% in experienced programs [43]. Early home discharge is common, and patients experience less pain, faster mobilization, and shorter hospital stays compared with conventional sternotomy CABG [44]. Long-term outcomes are also encouraging, with studies showing comparable survival to traditional CABG even in elderly patients [45]. These results highlight the potential for minimally invasive OPCAB to expand access to surgical revascularization for patients who might otherwise be considered high risk.

Robotic platforms offer additional advantages by enhancing visualization and instrument precision. Three-dimensional imaging, wristed instruments, and tremor filtration allow surgeons to perform delicate anastomoses through small ports. These capabilities are particularly valuable in OPCAB, where motion control and exposure are critical. As robotic systems continue to evolve, they may further reduce the technical barriers associated with beating-heart surgery.

The integration of OPCAB with minimally invasive and robotic techniques also aligns with patient preferences for less invasive procedures. As healthcare systems increasingly emphasize patient-centered care, minimally invasive OPCAB offers a compelling alternative to both conventional CABG and PCI. This represents a major opportunity for OPCAB to expand its role in the modern revascularization landscape.

Enhanced Intraoperative Imaging and Graft Verification

Advances in intraoperative imaging represent a major opportunity to improve OPCAB outcomes by addressing concerns about graft patency and anastomotic quality. TTFM has become an essential tool for assessing graft flow, pulsatility, and resistance. Studies have shown that TTFM-guided revisions can significantly reduce early graft failure, particularly in saphenous vein grafts and complex anastomoses [46]. By providing real-time feedback, TTFM enhances surgical precision and increases confidence in graft quality.

ICG fluorescence angiography offers another powerful imaging modality. ICG provides high-resolution visualization of graft patency and coronary perfusion, with sensitivity comparable to intraoperative angiography. Early studies demonstrated its utility in off-pump CABG, particularly for verifying composite grafts and sequential anastomoses [47–49]. ICG is fast, safe, and repeatable, making it well suited for routine use in OPCAB.

High-resolution epicardial ultrasound further enhances intraoperative assessment by providing detailed images of graft geometry, anastomotic integrity, and flow patterns. When combined with TTFM, epicardial ultrasound significantly increases diagnostic accuracy and reduces the likelihood of missed technical errors [50]. These imaging modalities collectively address one of the most persistent criticisms of OPCAB—its perceived risk of inferior graft patency.

The widespread adoption of intraoperative imaging could transform OPCAB by standardizing graft verification and reducing operator dependency. As imaging technologies become more accessible and integrated into surgical workflows, they may help bridge the gap between high-volume expert centers and lower-volume institutions. This represents a major opportunity to improve outcomes, increase surgeon confidence, and expand the use of OPCAB in diverse clinical settings.

Training, Subspecialization, and Standardization

The growing recognition of coronary surgery as a subspecialty presents a significant opportunity to improve OPCAB outcomes through structured training and standardization. Historically, variability in surgeon experience has been a major barrier to OPCAB adoption.

By concentrating expertise in high-volume centers and establishing dedicated training pathways, the surgical community can reduce variability and improve outcomes. Commentary from leading surgeons emphasizes the need for coronary surgery to be recognized as a distinct discipline with specialized skills and competencies [51-53].

Standardized training programs could include simulation-based practice, proctored cases, and competency-based assessments. These approaches have been successful in other surgical fields and could help shorten the learning curve for OPCAB. Additionally, the development of standardized protocols for exposure, stabilization, conduit selection, and intraoperative imaging would promote consistency across institutions. Such standardization could also facilitate multicenter trials, enabling more robust evaluation of OPCAB outcomes.

Subspecialization also creates opportunities for innovation and research [53]. Dedicated coronary surgeons are more likely to adopt advanced techniques such as anaortic grafting, composite arterial configurations, and minimally invasive approaches. They are also better positioned to integrate emerging technologies such as robotic platforms, artificial intelligence, and enhanced imaging. By fostering a culture of innovation, subspecialization can drive continuous improvement in OPCAB techniques and outcomes.

Finally, subspecialization may improve patient access to high-quality OPCAB. As expertise becomes concentrated in specialized centers, referral pathways can be streamlined, ensuring that patients who would benefit most from OPCAB—such as those with high stroke risk or severe comorbidities—receive appropriate care. This represents a major opportunity to enhance the overall quality and equity of coronary revascularization.

THREATS

Despite the significant opportunities for growth and refinement, OPCAB faces several external threats that could limit its long-term viability within the field of coronary revascularization. These threats arise from evolving clinical practice patterns, technological competition, institutional variability, and persistent skepticism regarding the technique’s durability. As the landscape of cardiovascular care continues to shift toward less invasive interventions and precision-guided therapies, OPCAB must demonstrate clear and consistent advantages to maintain relevance.

One of the most pressing threats is the decline in surgeon experience. As fewer centers perform OPCAB routinely, the number of surgeons proficient in beating-heart techniques continues to shrink. This creates a self-reinforcing cycle: reduced experience leads to inferior outcomes, which further discourages adoption. Without deliberate efforts to preserve and expand OPCAB expertise, the technique risks becoming marginalized, particularly in regions where on-pump CABG remains dominant.

Competition from PCI and HCR also poses a significant threat. Advances in drug-eluting stents, intravascular imaging, and physiologic assessment have expanded the indications for PCI, reducing the number of patients referred for surgical revascularization. HCR, which combines left internal thoracic artery-left anterior descending artery (LITA-LAD) grafting with PCI for non-LAD lesions, offers a minimally invasive alternative that may appeal to both patients and clinicians [54]. These evolving strategies challenge OPCAB's position within the broader revascularization ecosystem.

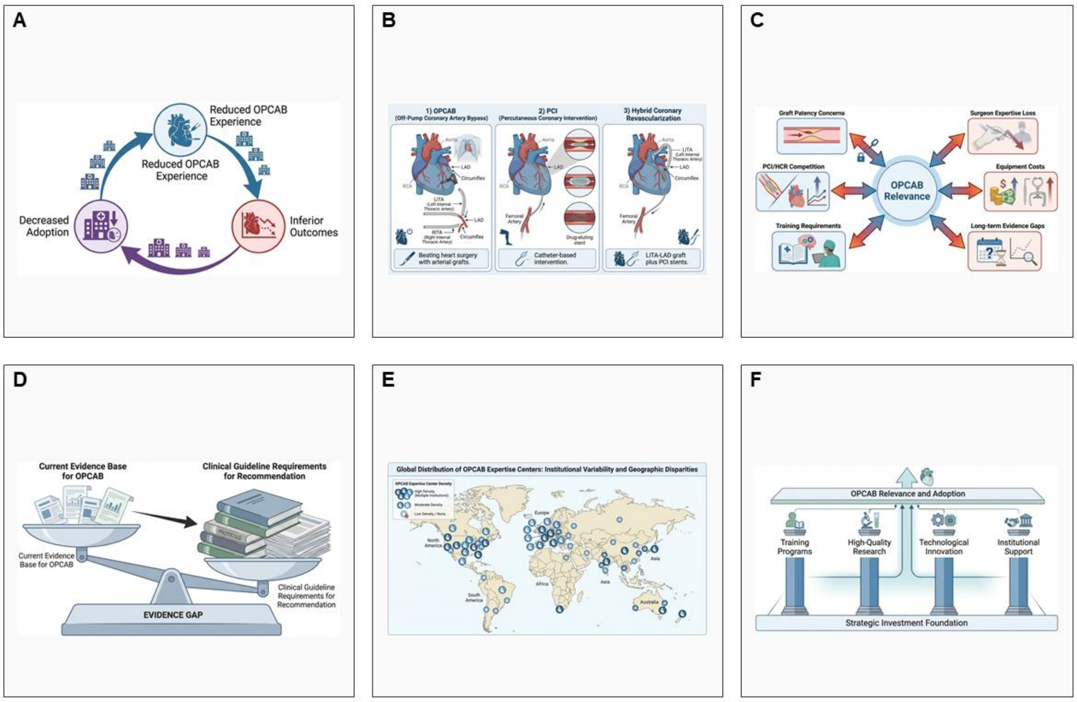

Figure 4. OPCAB Viability Threats and Competitive Landscape in Coronary Revascularization

(A) Self-reinforcing cycle of declining OPCAB experience and adoption.
(B) Three competing coronary revascularization strategies in modern practice.
(C) Interconnected threats to OPCAB viability and clinical adoption.
(D) Evidence gaps limiting OPCAB guideline recommendations and acceptance.
(E) Geographic and institutional disparities in OPCAB expertise distribution.
(F) Strategic investment areas needed to maintain OPCAB clinical relevance.

Finally, persistent concerns regarding graft patency, completeness of revascularization, and long-term outcomes continue to influence guideline recommendations and surgeon preferences [55]. Without robust, high-quality evidence demonstrating durable benefits, OPCAB may struggle to achieve widespread acceptance. Economic and technological barriers—such as the cost of specialized equipment and the need for dedicated training—further compound these challenges. Together, these threats underscore the need for strategic investment in training, research, and institutional support to ensure OPCAB's continued relevance (Figure 4).

Declining Surgeon Experience and Institutional Variability

One of the most significant threats to OPCAB is the steady decline in surgeon experience. As many institutions have shifted toward conventional on-pump CABG, the number of surgeons performing OPCAB regularly has decreased. This decline is problematic because OPCAB outcomes are highly operator-dependent. Surgeons who perform only a handful of OPCAB cases per year are unlikely to maintain the technical proficiency required for optimal results [4]. This variability in experience contributes to inconsistent outcomes across institutions and reinforces skepticism regarding the technique.

Institutional variability further exacerbates this issue. Successful OPCAB requires not only a skilled surgeon but also a coordinated multidisciplinary team, including anesthesiologists, nurses, and perfusionists familiar with beating-heart techniques. Centers that lack this infrastructure may experience higher rates of conversion to CPB, incomplete revascularization, or graft failure. These challenges create a perception that OPCAB is inherently less reliable than on-pump CABG, even though high-volume centers consistently demonstrate excellent outcomes [38].

The decline in OPCAB experience also has implications for training. As fewer surgeons perform OPCAB, opportunities for trainees to gain hands-on experience diminish. This threatens the development of the next generation of OPCAB surgeons and may lead to a further erosion of expertise [56]. Without deliberate efforts to incorporate OPCAB into training curricula and maintain procedural volume, the technique risks becoming a niche skill practiced only in a handful of specialized centers.

Finally, declining experience creates a negative feedback loop. Poor outcomes in low-volume centers reinforce the perception that OPCAB is inferior, leading to further reductions in case volume and training opportunities. Breaking this cycle will require institutional commitment, structured training programs, and recognition of coronary surgery as a subspecialty with distinct competencies.

Competition from PCI and Hybrid Revascularization

Advances in PCI technology represent a major threat to the long-term viability of OPCAB. Modern drug-eluting stents (DES), intravascular ultrasound (IVUS), optical coherence tomography (OCT), and physiologic assessment tools such as fractional flow reserve (FFR) have dramatically improved PCI outcomes [57,58]. As a result, many patients who previously would have been referred for CABG are now managed percutaneously. This shift reduces the overall volume of surgical revascularization and limits opportunities for OPCAB.

Hybrid coronary revascularization further challenges OPCAB's role. HCR combines the durability of LITA-LAD grafting with PCI for non-LAD lesions, offering a minimally invasive alternative to multivessel CABG. Studies have shown that HCR can achieve comparable outcomes to conventional CABG while reducing surgical trauma and facilitating faster recovery [59–61]. For patients and clinicians seeking less invasive options, HCR may be more appealing than OPCAB, particularly in centers with established hybrid programs.

The growing popularity of minimally invasive and robotic techniques also influences the competitive landscape. While these approaches can be integrated with OPCAB, they are often marketed as distinct alternatives. Patients may perceive robotic or hybrid procedures as more advanced or less invasive, even when OPCAB offers comparable or superior outcomes. This perception can influence referral patterns and reduce the number of patients considered for beating-heart surgery.

Finally, the rapid pace of innovation in PCI and hybrid techniques may outstrip the rate of advancement in OPCAB. Without continued investment in technology, training, and research, OPCAB risks being overshadowed by less invasive strategies that offer similar or better outcomes in selected patients. This competitive pressure underscores the need for OPCAB to demonstrate clear advantages in specific patient populations, such as those at high risk for stroke or CPB-related complications.

Persistent Skepticism Regarding Patency and Completeness of Revascularization

Despite improvements in technique and technology, skepticism regarding OPCAB's graft patency and completeness of revascularization remains widespread. This skepticism is rooted in early randomized trials and meta-analyses that reported higher rates of graft occlusion and incomplete revascularization with OPCAB compared with on-pump CABG [5,36]. Although high-volume centers have demonstrated excellent outcomes, the variability in results across institutions has reinforced concerns about the technique's reliability.

These concerns influence both surgeon behavior and guideline recommendations. Many surgeons remain hesitant to perform OPCAB in patients with complex multivessel disease, small target vessels, or diffuse atherosclerosis. Guideline committees have also been cautious, often recommending OPCAB only in selected patients or when performed by experienced surgeons [62]. This limited endorsement reduces the number of patients considered for OPCAB and contributes to declining procedural volumes.

Skepticism regarding patency also affects patient perceptions. Patients may be reluctant to undergo OPCAB if they believe it carries a higher risk of graft failure or incomplete revascularization. This perception is often reinforced by referring cardiologists, who may favor PCI or conventional CABG based on their understanding of the evidence. Overcoming this skepticism will require robust, high-quality data demonstrating the long-term durability of OPCAB, particularly when performed using arterial and anaortic grafting strategies.

Finally, skepticism creates a barrier to innovation. Surgeons and institutions may be less willing to invest in OPCAB-related technologies, training, or research if they perceive the technique as inferior or outdated. This lack of investment further limits opportunities for improvement and perpetuates the cycle of skepticism. Addressing these concerns will require a concerted effort to standardize techniques, incorporate intraoperative imaging, and generate high-quality evidence.

Technological and Economic Barriers to Widespread Adoption

OPCAB requires specialized equipment, including stabilizers, positioners, and advanced exposure devices. These tools are essential for achieving high-quality anastomoses on a beating heart, but they add cost and complexity to the procedure. In resource-limited settings, the expense of acquiring and maintaining this equipment may be prohibitive. Even in well-resourced institutions, budgetary constraints and competing priorities can limit investment in OPCAB infrastructure.

Economic barriers also extend to training. Developing and maintaining OPCAB expertise requires dedicated training programs, simulation facilities, and proctored cases. These investments may be difficult to justify in institutions with low procedural volumes or limited interest in beating-heart surgery. As a result, many centers lack the resources needed to support consistent OPCAB practice, contributing to variability in outcomes.

Technological barriers further complicate adoption. While advances in imaging, robotics, and minimally invasive techniques offer opportunities for OPCAB integration, they also require significant capital investment. Institutions may prioritize technologies perceived as more innovative or broadly applicable, such as robotic platforms or hybrid operating rooms. Without clear evidence demonstrating the cost-effectiveness of OPCAB, these competing priorities may limit its adoption [63].

Finally, economic pressures within healthcare systems may favor shorter, more predictable procedures. OPCAB can be more time-consuming and technically challenging than on-pump CABG, particularly in complex cases. In environments where operating room efficiency is closely monitored, these factors may discourage surgeons from performing OPCAB. Addressing these barriers will require demonstrating the long-term value of OPCAB in reducing complications, improving outcomes, and optimizing resource utilization.

CONCLUSION

Off-pump coronary artery bypass grafting occupies a complex but strategically important position in contemporary coronary surgery. Its strengths—particularly the reduction in neurological complications, attenuation of systemic inflammation, and compatibility with anaortic total arterial revascularization—are well supported by robust evidence. These advantages are especially relevant in high-risk populations, including patients with severe aortic calcification, chronic kidney disease, chronic obstructive pulmonary disease, and left ventricular dysfunction. In these groups, OPCAB offers a physiologically gentler alternative to conventional on-pump CABG, with demonstrable reductions in perioperative morbidity.

However, OPCAB's weaknesses remain significant and cannot be overlooked. Operator dependency, technical complexity, concerns regarding graft patency, and inconsistent long-term outcomes have limited its widespread adoption. These challenges are compounded by variability in institutional expertise and the steep learning curve associated with beating-heart surgery. While high-volume centers consistently report excellent results, the heterogeneity of outcomes across institutions underscores the need for standardized training, intraoperative imaging, and structured quality assurance.

At the same time, OPCAB faces both opportunities and threats that will shape its future trajectory. The expansion of anaortic no-touch techniques, integration with minimally invasive and robotic platforms, and advances in intraoperative imaging offer promising avenues for improving outcomes and expanding indications. Conversely, competition from PCI and hybrid revascularization, declining surgeon experience, and economic barriers pose real challenges to OPCAB's long-term viability. Addressing these threats will require strategic investment in training, research, and institutional support.

Ultimately, OPCAB should not be viewed as a universal replacement for on-pump CABG, but rather as a complementary technique with distinct advantages in selected patients. Its future depends on the ability of the surgical community to refine training pathways, embrace technological innovation, and generate high-quality evidence that clarifies its long-term benefits. With thoughtful integration into modern revascularization strategies, OPCAB can continue to play a vital role in optimizing outcomes for patients with coronary artery disease.

CRediT Author Statement

Amna Zafar: Writing – Original Draft; Writing – Review & Editing; Final Approval of the Manuscript.

Shahzad G. Raja: Conceptualization; Methodology; Supervision; Writing – Original Draft; Writing – Review & Editing; Project Administration; Final Approval of the Manuscript.

Conflict of Interest

The authors declare no conflicts of interest related to this work.

Funding

No funding was received for the preparation of this manuscript.

REFERENCES

1. Gilbey T, Milne B, de Somer F, Kunst G. Neurologic complications after cardiopulmonary bypass - A narrative review. Perfusion. 2023;38:1545-1559. doi: 10.1177/02676591221119312.
2. Guida GA, Chivasso P, Fudulu D, Rapetto F, Sedmakov C, Marsico R, Zakkar M, Bryan AJ, Angelini GD. Off-pump coronary artery bypass grafting in high-risk patients: a review. J Thorac Dis. 2016;8(Suppl 10):S795-S798. doi: 10.21037/jtd.2016.10.107.
3. Yoo KJ. The Past, Present, and Future of Off-Pump Coronary Artery Bypass Grafting. J Chest Surg. 2025;58:121-133. doi: 10.5090/jcs.24.122.
4. Gaudino M, Benedetto U, Bakaeen F, Rahouma M, Tam DY, Abouarab A, Di Franco A, Leonard J, Elmously A, Puskas JD, Angelini GD, Girardi LN, Fremes SE, Taggart DP. Off- Versus On-Pump Coronary Surgery and the Effect of Follow-Up Length and Surgeons' Experience: A Meta-Analysis. J Am Heart Assoc. 2018;7:e010034. doi: 10.1161/JAHA.118.010034.
5. Zhou Z, Fu G, Feng K, Huang S, Chen G, Liang M, Wu Z. Randomized evidence on graft patency after off-pump versus on-pump coronary artery bypass grafting: An updated meta-analysis. Int J Surg. 2022;98:106212. doi: 10.1016/j.ijsu.2021.106212.
6. Takagi H, Umemoto T; All-Literature Investigation of Cardiovascular Evidence (ALICE) Group. Worse long-term survival after off-pump than on-pump coronary artery bypass grafting. J Thorac Cardiovasc Surg. 2014;148:1820-9. doi: 10.1016/j.jtcvs.2014.05.034.

7. Ikeda M, Niinami H, Morita K, Saito S, Yoshitake A. Long-term results following off-pump coronary-artery bypass grafting in left ventricular dysfunction. Heart Vessels. 2024;39:571-581. doi: 10.1007/s00380-024-02383-9.
8. Hannan EL, Wu C, Smith CR, Higgins RS, Carlson RE, Culliford AT, Gold JP, Jones RH. Off-pump versus on-pump coronary artery bypass graft surgery: differences in short-term outcomes and in long-term mortality and need for subsequent revascularization. Circulation. 2007;116:1145-52. doi: 10.1161/CIRCULATIONAHA.106.675595.
9. Bakaeen FG, Shroyer AL, Gammie JS, Sabik JF, Cornwell LD, Coselli JS, Rosengart TK, O'Brien SM, Wallace A, Shahian DM, Grover FL, Puskas JD. Trends in use of off-pump coronary artery bypass grafting: Results from the Society of Thoracic Surgeons Adult Cardiac Surgery Database. J Thorac Cardiovasc Surg. 2014;148:856-3, 864.e1; discussion 863-4. doi: 10.1016/j.jtcvs.2013.12.047.
10. Pawliszak W, Kowalewski M, Raffa GM, Malvindi PG, Kowalkowska ME, Szwed KA, Borkowska A, Kowalewski J, Anisimowicz L. Cerebrovascular Events After No-Touch Off-Pump Coronary Artery Bypass Grafting, Conventional Side-Clamp Off-Pump Coronary Artery Bypass, and Proximal Anastomotic Devices: A Meta-Analysis. J Am Heart Assoc. 2016;5:e002802. doi: 10.1161/JAHA.115.002802.
11. Fazmin IT, Ali JM. Hybrid Coronary Revascularisation: Indications, Techniques, and Outcomes. J Clin Med. 2025;14:880. doi: 10.3390/jcm14030880.
12. Prapas S, Calafiore AM, Katsavrias KP, Panagiotopoulos IA, Linardakis IN, Tancredi F, Foschi M, Di Mauro M. Anaortic coronary surgery using the Π-circuit is associated with a low incidence of perioperative neurological complications. Eur J Cardiothorac Surg. 2018;54:884-888. doi: 10.1093/ejcts/ezy224.
13. Kroeze VJ, Olsthoorn JR, van Straten AHM, Princee A, Soliman-Hamad MA. Predictors and Outcomes of Stroke After Isolated Coronary Artery Bypass Grafting. A Single-Center Experience in 20,582 Patients. J Cardiothorac Vasc Anesth. 2023;37:1397-1402. doi: 10.1053/j.jvca.2023.04.012.
14. Lev-Ran O, Ben-Gal Y, Matsa M, Paz Y, Kramer A, Pevni D, Locker C, Uretzky G, Mohr R. 'No touch' techniques for porcelain ascending aorta: comparison between cardiopulmonary bypass with femoral artery cannulation and off-pump myocardial revascularization. J Card Surg. 2002;17:370-6. doi: 10.1111/j.1540-8191.2001.tb01161.x.
15. Cappellaro AP, de Almeida LFC, Pinto ML, Martins MAB, Sousa AGE, Gadelha JG, Vieira ACP, Rocha LFR, Thet MS. Off-pump versus on-pump coronary artery bypass grafting in patients with chronic obstructive pulmonary disease: a systematic review and meta-analysis. Gen Thorac Cardiovasc Surg. 2025;73:201-208. doi: 10.1007/s11748-025-02116-3.
16. Wang Y, Zhu S, Gao P, Zhou J, Zhang Q. Off-pump versus on-pump coronary surgery in patients with chronic kidney disease: a meta-analysis. Clin Exp Nephrol. 2018;22:99-109. doi: 10.1007/s10157-017-1432-7.
17. Raja SG. Total arterial off-pump coronary revascularization: The Holy Grail? Curr Opin Cardiol. 2019;34:552-556. doi: 10.1097/HCO.0000000000000645.
18. Lorusso R, Moscarelli M, Di Franco A, Grazioli V, Nicolini F, Gherli T, De Bonis M, Taramasso M, Villa E, Troise G, Scrofani R, Antona C, Mariscalco G, Beghi C, Miceli A, Glauber M, Ranucci M, De Vincentiis C, Gaudino M. Association Between Coronary Artery Bypass Surgical Techniques and Postoperative Stroke. J Am Heart Assoc. 2019;8:e013650. doi: 10.1161/JAHA.119.013650.
19. Gelsomino S, Tetta C, Matteucci F, Del Pace S, Parise O, Prifti E, Dokollari A, Parise G, Micali LR, La Meir M, Bonacchi M. Surgical Risk Factors for Ischemic Stroke Following Coronary Artery

Bypass Grafting. A Multi-Factor Multimodel Analysis. Front Cardiovasc Med. 2021;8:622480. doi: 10.3389/fcvm.2021.622480.

20. Zhao DF, Edelman JJ, Seco M, Bannon PG, Wilson MK, Byrom MJ, Thourani V, Lamy A, Taggart DP, Puskas JD, Vallely MP. Coronary Artery Bypass Grafting With and Without Manipulation of the Ascending Aorta: A Network Meta-Analysis. J Am Coll Cardiol. 2017;69:924-936. doi: 10.1016/j.jacc.2016.11.071.
21. Albert A, Ennker J, Hegazy Y, Ullrich S, Petrov G, Akhyari P, Bauer S, Ürer E, Ennker IC, Lichtenberg A, Priss H, Assmann A. Implementation of the aortic no-touch technique to reduce stroke after off-pump coronary surgery. J Thorac Cardiovasc Surg. 2018;156:544-554.e4. doi: 10.1016/j.jtcvs.2018.02.111.
22. Ascione R, Ghosh A, Reeves BC, Arnold J, Potts M, Shah A, Angelini GD. Retinal and cerebral microembolization during coronary artery bypass surgery: a randomized, controlled trial. Circulation. 2005;112:3833-8. doi: 10.1161/CIRCULATIONAHA.105.557462.
23. Ahmed M, Majeed K, Ali H, Syed H, Batool A. Off-pump vs. on-pump coronary artery bypass grafting in patients with chronic kidney disease: an updated systematic review and meta-analysis. Int Urol Nephrol. 2025;57:463-477. doi: 10.1007/s11255-024-04198-z.
24. Guan Z, Guan X, Gu K, Lin X, Lin J, Zhou W, Xu M, Wan F, Zhang Z, Song C. Short-term outcomes of on- vs off-pump coronary artery bypass grafting in patients with left ventricular dysfunction: a systematic review and meta-analysis. J Cardiothorac Surg. 2020;15:84. doi: 10.1186/s13019-020-01115-0.
25. Wang C, Jiang Y, Wang Q, Wang D, Jiang X, Dong N, Chen S, Chen X. Off-pump versus on-pump coronary artery bypass grafting in elderly patients at 30 days: a propensity score matching study. Postgrad Med J. 2024;100:414-420. doi: 10.1093/postmj/qgad120.
26. Paparella D, Yau TM, Young E. Cardiopulmonary bypass induced inflammation: pathophysiology and treatment. An update. Eur J Cardiothorac Surg. 2002;21:232-44. doi: 10.1016/s1010-7940(01)01099-5.
27. Møller CH, Penninga L, Wetterslev J, Steinbrüchel DA, Gluud C. Off-pump versus on-pump coronary artery bypass grafting for ischaemic heart disease. Cochrane Database Syst Rev. 2012;2012:CD007224. doi: 10.1002/14651858.CD007224.pub2.
28. Ascione R, Williams S, Lloyd CT, Sundaramoorthi T, Pitsis AA, Angelini GD. Reduced postoperative blood loss and transfusion requirement after beating-heart coronary operations: a prospective randomized study. J Thorac Cardiovasc Surg. 2001;121:689-96. doi: 10.1067/mtc.2001.112823.
29. Ascione R, Lloyd CT, Underwood MJ, Lotto AA, Pitsis AA, Angelini GD. Inflammatory response after coronary revascularization with or without cardiopulmonary bypass. Ann Thorac Surg. 2000;69:1198-204. doi: 10.1016/s0003-4975(00)01152-8.
30. Yamaguchi A, Endo H, Kawahito K, Adachi H, Ino T. Off-pump coronary artery bypass grafting attenuates proinflammatory markers. Jpn J Thorac Cardiovasc Surg. 2005;53:127-32. doi: 10.1007/s11748-005-0017-7.
31. Speziale G, Ruvolo G, Coppola R, Marino B. Intraoperative flow measurement in composite Y arterial grafts. Eur J Cardiothorac Surg. 2000;17:505-8. doi: 10.1016/s1010-7940(00)00395-x.
32. Kawajiri H, Grau JB, Fortier JH, Glineur D. Bilateral internal thoracic artery grafting: *in situ* or composite? Ann Cardiothorac Surg. 2018;7:673-680. doi: 10.21037/acs.2018.05.16.

33. Kim KB, Hwang SW, Kim MS. Techniques and Outcomes of the No-Touch Vein Conduit as a Y-Composite Graft. Braz J Cardiovasc Surg. 2022;37(Spec 1):38-41. doi: 10.21470/1678-9741-2022-0119.

34. Puskas JD, Thourani VH, Kilgo P, Cooper W, Vassiliades T, Vega JD, Morris C, Chen E, Schmotzer BJ, Guyton RA, Lattouf OM. Off-pump coronary artery bypass disproportionately benefits high-risk patients. Ann Thorac Surg. 2009;88:1142-7. doi: 10.1016/j.athoracsur.2009.04.135.

35. Hattler B, Messenger JC, Shroyer AL, Collins JF, Haugen SJ, Garcia JA, Baltz JH, Cleveland JC Jr, Novitzky D, Grover FL; Veterans Affairs Randomized On/Off Bypass (ROOBY) Study Group. Off-Pump coronary artery bypass surgery is associated with worse arterial and saphenous vein graft patency and less effective revascularization: Results from the Veterans Affairs Randomized On/Off Bypass (ROOBY) trial. Circulation. 2012;125:2827-35. doi: 10.1161/CIRCULATIONAHA.111.069260.

36. He L, Tiemuerniyazi X, Chen L, Yang Z, Huang S, Nan Y, Song Y, Feng W. Clinical outcomes of on-pump versus off-pump coronary-artery bypass surgery: a meta-analysis. Int J Surg. 2024;110:5063-5070. doi: 10.1097/JS9.0000000000001481.

37. Razavi AA, Malas J, Salam A, Emerson DA, Bowdish ME. Off-Pump Coronary Artery Bypass Grafting is Overutilized. Semin Thorac Cardiovasc Surg. 2025;37:43-47. doi: 10.1053/j.semtcvs.2024.12.001.

38. Naito S, Demal TJ, Sill B, Reichenspurner H, Onorati F, Gatti G, Mariscalco G, Faggian G, Salsano A, Santini F, Santarpino G, Zanobini M, Musumeci F, Rubino AS, Bancone C, De Feo M, Nicolini F, Dalén M, Speziale G, Bounader K, Mäkikallio T, Tauriainen T, Ruggieri VG, Perrotti A, Biancari F. Impact of Surgeon Experience and Centre Volume on Outcome After Off-Pump Coronary Artery Bypass Surgery: Results From the European Multicenter Study on Coronary Artery Bypass Grafting (E-CABG) Registry. Heart Lung Circ. 2023;32:387-394. doi: 10.1016/j.hlc.2022.11.009.

39. Taggart DP, Gaudino MF, Gerry S, Gray A, Lees B, Sajja LR, Zamvar V, Flather M, Benedetto U; Arterial Revascularization Trial Investigators. Ten-year outcomes after off-pump versus on-pump coronary artery bypass grafting: Insights from the Arterial Revascularization Trial. J Thorac Cardiovasc Surg. 2021;162:591-599.e8. doi: 10.1016/j.jtcvs.2020.02.035.

40. Marczin N, Raja SG. Off-pump coronary artery bypass grafting. AME Med J 2020;5:21. doi: 10.21037/amj.2020.03.11.

41. Raja SG, Benedetto U. Off-pump coronary artery bypass grafting: Misperceptions and misconceptions. World J Methodol. 2014;4:6-10. doi: 10.5662/wjm.v4.i1.6.

42. Comanici M, Bulut HI, Raja SG. 10-Year Mortality of Off-Pump Versus On-Pump Coronary Artery Bypass Grafting: An Updated Systematic Review, Meta-Analysis, and Meta-Regression. Am J Cardiol. 2024;219:77-84. doi: 10.1016/j.amjcard.2024.03.019.

43. Walton AJ, Pineda AM, Rogers L, Davierwala PM, Zwischenberger BA. Review of minimally invasive coronary artery bypass grafting. Eur J Cardiothorac Surg. 2025;67:ezaf160. doi: 10.1093/ejcts/ezaf160.

44. Spanjersberg A, Hoek L, Ottervanger JP, Nguyen TY, Kaplan E, Laurens R, Singh S. Early home discharge after robot-assisted coronary artery bypass grafting. Interact Cardiovasc Thorac Surg. 2022;35:ivac134. doi: 10.1093/icvts/ivac134.

45. Barsoum EA, Azab B, Shah N, Patel N, Shariff MA, Lafferty J, Nabagiez JP, McGinn JT Jr. Long-term mortality in minimally invasive compared with sternotomy coronary artery bypass surgery in the geriatric population (75 years and older patients). Eur J Cardiothorac Surg. 2015;47:862-7. doi: 10.1093/ejcts/ezu267.

46. Niclauss L. Techniques and standards in intraoperative graft verification by transit time flow measurement after coronary artery bypass graft surgery: a critical review. Eur J Cardiothorac Surg. 2017;51:26-33. doi: 10.1093/ejcts/ezw203.
47. Reuthebuch O, Häussler A, Genoni M, Tavakoli R, Odavic D, Kadner A, Turina M. Novadaq SPY: intraoperative quality assessment in off-pump coronary artery bypass grafting. Chest. 2004;125:418-24. doi: 10.1378/chest.125.2.418.
48. Taggart DP, Choudhary B, Anastasiadis K, Abu-Omar Y, Balacumaraswami L, Pigott DW. Preliminary experience with a novel intraoperative fluorescence imaging technique to evaluate the patency of bypass grafts in total arterial revascularization. Ann Thorac Surg. 2003;75:870-3. doi: 10.1016/s0003-4975(02)04669-6.
49. Waseda K, Ako J, Hasegawa T, Shimada Y, Ikeno F, Ishikawa T, Demura Y, Hatada K, Yock PG, Honda Y, Fitzgerald PJ, Takahashi M. Intraoperative fluorescence imaging system for on-site assessment of off-pump coronary artery bypass graft. JACC Cardiovasc Imaging. 2009;2:604-12. doi: 10.1016/j.jcmg.2008.12.028.
50. Di Giammarco G, Canosa C, Foschi M, Rabozzi R, Marinelli D, Masuyama S, Ibrahim BM, Ranalletta RA, Penco M, Di Mauro M. Intraoperative graft verification in coronary surgery: increased diagnostic accuracy adding high-resolution epicardial ultrasonography to transit-time flow measurement. Eur J Cardiothorac Surg. 2014;45:e41-5. doi: 10.1093/ejcts/ezt580.
51. Raja SG. Multiple Arterial Grafting in CABG: Outcomes, Concerns, and Controversies. J Vasc Dis.. 2025;4:29. doi: 10.3390/jvd4030029.
52. Bakaeen FG, Johnston DR, Svensson LG. Commentary: Coronary artery bypass grafting as a subspecialty: Hype or reality. J Thorac Cardiovasc Surg. 2021;161:2136-2137. doi: 10.1016/j.jtcvs.2020.04.013.
53. Gradinariu G, Raja SG. Myocardial surgical revascularization as a subspecialty: to be or not to be, that is the question. Vessel Plus. 2021;5:22. doi: 10.20517/2574-1209.2020.86.
54. Thielmann M, Bonaros N, Barbato E, Barili F, Folliguet T, Friedrich G, Gottardi R, Legutko J, Parolari A, Punjabi P, Sandner S, Suwalski P, Shehada SE, Wendt D, Czerny M, Muneretto C. Hybrid coronary revascularization: position paper of the European Society of Cardiology Working Group on Cardiovascular Surgery and European Association of Percutaneous Cardiovascular Interventions. Eur J Cardiothorac Surg. 2024;66:ezae271. doi: 10.1093/ejcts/ezae271.
55. Shroyer AL, Grover FL, Hattler B, Collins JF, McDonald GO, Kozora E, Lucke JC, Baltz JH, Novitzky D; Veterans Affairs Randomized On/Off Bypass (ROOBY) Study Group. On-pump versus off-pump coronary-artery bypass surgery. N Engl J Med. 2009 Nov 5;361(19):1827-37. doi: 10.1056/NEJMoa0902905.
56. Comanici M, Soni M, Raja SG. Trainee Perceptions of Off-Pump Coronary Artery Bypass Grafting: United Kingdom Training Needs Survey. Am J Cardiol. 2024;220:47-48. doi: 10.1016/j.amjcard.2024.03.031.
57. Mandurino-Mirizzi A, Munafò AR, Rizzo F, Raone L, Germinal F, Montalto C, Mussardo M, Vergallo R, Fischetti D, Godino C, Colonna G, Oreglia J, Burzotta F, Crimi G, Porto I. Comparison of different guidance strategies to percutaneous coronary intervention: A network meta-analysis of randomized clinical trials. Int J Cardiol. 2025;422:132936. doi: 10.1016/j.ijcard.2024.132936.
58. Lingamsetty SSP, Doma M, Kritya M, Thyagaturu H, Ubaid M, Jitta SR, Prajapati K, Ramadan A, Al-Shammari AS, Martignoni FV, Seto A, Shlofmitz E, Basir MB, Megaly MS, Goldsweig AM. Mechanical outcomes of coronary stenting guided by intravascular ultrasound versus optical

coherence tomography: A systematic review and meta-analysis with trial sequential analysis of randomized trials. Int J Cardiol. 2025;435:133387. doi: 10.1016/j.ijcard.2025.133387.

59. Yu L, Zhu K, Du N, Si Y, Liang J, Shen R, Chen B. Comparison of hybrid coronary revascularization versus coronary artery bypass grafting in patients with multivessel coronary artery disease: a meta-analysis. J Cardiothorac Surg. 2022;17:147. doi: 10.1186/s13019-022-01903-w.

60. Tajstra M, Hrapkowicz T, Hawranek M, Filipiak K, Gierlotka M, Zembala M, Gąsior M, Zembala MO; POL-MIDES Study Investigators. Hybrid Coronary Revascularization in Selected Patients With Multivessel Disease: 5-Year Clinical Outcomes of the Prospective Randomized Pilot Study. JACC Cardiovasc Interv. 2018;11:847-852. doi: 10.1016/j.jcin.2018.01.271.

61. Ganyukov VI, Kochergin NA, Shilov AA, Tarasov RS, Kozyrin KA, Prokudina ES, Barbarash OL, Barbarash LS. Randomized Clinical Trial of Hybrid vs. Surgical vs. Percutaneous Multivessel Coronary Revascularization: 5-year Follow-up of HREVS Trial. Kardiologiia. 2023 Dec 5;63(11):57-63. Russian, English. doi: 10.18087/cardio.2023.11.n2475.

62. Neumann FJ, Sousa-Uva M, Ahlsson A, Alfonso F, Banning AP, Benedetto U, Byrne RA, Collet JP, Falk V, Head SJ, Jüni P, Kastrati A, Koller A, Kristensen SD, Niebauer J, Richter DJ, Seferovic PM, Sibbing D, Stefanini GG, Windecker S, Yadav R, Zembala MO; ESC Scientific Document Group. 2018 ESC/EACTS Guidelines on myocardial revascularization. Eur Heart J. 2019;40:87-165. doi: 10.1093/eurheartj/ehy394.

63. Gianoli M, de Jong AR, van der Harst P, van der Kaaij NP, Jacob KA, Suyker WJL. Cost Analysis of Robot-Assisted Versus On-Pump and Off-Pump Coronary Artery Bypass Grafting: A Single-Center Surgical and 30-Day Outcomes Comparison. Innovations (Phila). 2024;19:416-424. doi: 10.1177/15569845241269312.