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On-Pump Versus Off-Pump Coronary Artery Bypass Grafting: A Comparison of Outcomes in Patients Receiving LIMA-LAD and Sequential No-Touch Saphenous Vein Graft Anastomoses

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AIM: Coronary artery bypass grafting (CABG), whether conducted using on-pump or off-pump strategies, exhibits distinct perioperative risk profiles. When combined with left internal mammary artery (LIMA) to left anterior descending artery (LAD) grafting and sequential no-touch saphenous vein graft (SVG) anastomosis, these differences gain clinical relevance. Therefore, this study aims to compare the clinical outcomes of on-pump CABG and off-pump CABG in patients who uniformly received the LIMA-LAD graft combined with sequential no-touch SVG anastomosis.

METHODS: This retrospective cohort study included 240 patients who received LIMA-LAD grafting combined with sequential no-touch SVG anastomosis between June 2019 and December 2023. Of the total patients, 61 received the procedure under cardiopulmonary bypass and were assigned to the on-pump group, while 179 underwent off-pump coronary artery bypass, categorized as the off-pump group. After propensity score matching (PSM; 1:1 ratio), 57 pairs were successfully matched and analyzed. The primary endpoint of the study included the incidence of major adverse cardiovascular and cerebrovascular events (MACCE), a composite of all-cause mortality, myocardial infarction, stroke, or target vessel revascularization, within one year after surgery. A key secondary endpoint was a graft patency rate assessed within one year after the procedure, including the LIMA-LAD graft and the sequential SVGs. Other secondary endpoints included: (1) postoperative recovery metrics, such as intensive care unit (ICU) stay duration, duration of mechanical ventilation, volume of thoracic drainage, and blood transfusion requirements; (2) hemodynamic parameters at 24 hours post-operation, including cardiac index (CI), pulmonary artery wedge pressure (PAWP), left ventricular stroke work index (LVSWI), stroke volume index (SVI), mean arterial pressure (MAP), and systemic vascular resistance index (SVRI); and (3) short-term postoperative complications (e.g., atrial fibrillation, acute kidney injury (AKI), sternal wound infection, and lower extremity venous territory infection).

RESULTS: There was no significant difference in the one-year incidence of MACCE between the off-pump and on-pump groups ($p > 0.05$). Similarly, no significant differences were found in the one-year patency rates of the LIMA-LAD graft or the sequential SVGs between the two groups ($p > 0.05$). Compared to the on-pump group, the off-pump group had shorter ICU stays, reduced duration of mechanical ventilation, lower thoracic drainage volumes, and decreased blood transfusion requirements ($p < 0.001$). Furthermore, no significant difference was observed in total hospitalization duration between the two groups ($p > 0.05$). Preoperatively, none of the hemodynamic parameters achieved statistical significance between the two groups ($p > 0.05$). At 24 hours postoperatively, both groups showed substantial within-group improvements (off-pump: all parameters; on-pump: CI, PAWP, LVSWI, SVRI; $p < 0.05$). However, between-group comparisons revealed better CI, PAWP, LVSWI, SVI and SVRI levels in the off-pump group ($p < 0.05$). Within 1 month postoperatively, the off-pump group experienced a lower incidence of atrial fibrillation ($p < 0.05$). Additionally, there were no significant differences in the rates of AKI, sternal wound infection, or leg wound infection between the two groups within 2 months postoperatively ($p > 0.05$).

CONCLUSIONS: Compared to on-pump CABG, off-pump CABG utilizing sequential no-touch SVG anastomosis offers advantages in terms of earlier recovery and superior hemodynamic performance without compromising graft patency or increasing the long-term risk of major adverse cardiovascular and cerebrovascular events.

Keywords: coronary artery bypass grafting; off-pump; cardiopulmonary bypass; hemodynamics; adverse cardiac event; cerebrovascular disease

Introduction

Atherosclerotic coronary heart disease (coronary artery disease [CAD]) is one of the leading causes of morbidity and mortality worldwide. It results from myocardial ischemia and hypoxia due to atherosclerotic lesions in the coronary arteries, leading to luminal stenosis or occlusion [1,2]. Changes in dietary habits, inactive lifestyles, and population aging contributed to a significant increase in the incidence and mortality of atherosclerotic CAD, with a considerable trend toward younger onset. The growing disease burden imposes significant healthcare and economic costs [3,4]. While traditional coronary artery bypass grafting (CABG) using cardiopulmonary bypass (CPB) is a well-established treatment approach, it can induce systemic inflammatory responses, coagulation dysfunctions,

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and ischemia-reperfusion injury, thereby increasing perioperative risks, especially in elderly individuals or those with impaired cardiac function [5].

Off-pump coronary artery bypass (OPCAB) is performed on a beating heart without using CPB, theoretically reducing CPB-related complications. Studies have demonstrated that OPCAB can reduce postoperative complications, decrease blood transfusion needs, and promote postoperative recovery [6,7]. However, this approach presents technical challenges, particularly hemodynamic fluctuations during cardiac displacement, with hypotension and oxygen desaturation during anastomosis of the circumflex artery [8].

Beyond the selection of circulatory strategy, long-term outcomes of CABG depend heavily on the quality and accuracy of the anastomotic technique. The left internal mammary artery (LIMA) to left anterior descending artery (LAD) graft, widely known as the "gold standard", is widely preferred due to its excellent patency rates [9,10]. However, in cases of multivessel disease, saphenous vein grafts (SVGs) are frequently required. Conventional harvesting of SVG usually damages the endothelium through mechanical traction and ischemia, compromising long-term patency [11]. The "no-touch" harvesting technique, which preserves perivenous fat and adventitia, reduces vasospasm and injury to the intima, thereby improving graft flow and patient outcomes [12]. Additionally, sequential anastomosis, where a single SVG serves multiple targets, reduces the number of aortic anastomoses, conserves conduit material, and shortens procedure time [13].

Although OPCAB and advanced graft techniques offer substantial advantages, a systematic comparative evaluation of their combined application remains limited. The combined use of LIMA-LAD grafting with no-touch SVG harvesting and sequential anastomosis under both on-pump coronary artery bypass (ONCAB) and off-pump coronary artery bypass (OPCAB) conditions has not been comprehensively examined. Existing studies primarily focus on techniques in isolation: sequential SVG has demonstrated favorable safety and efficacy with potentially superior long-term patency as a secondary graft option [14]; the no-touch SVG strategy has revealed promising short-term patency in OPCAB [15]; and sequential venous grafts using the no-touch technique have been found both safe and effective in OPCAB [16]. Nevertheless, the overall impact of combining these strategies, such as integrating LIMA-LAD grafting, no-touch SVG, and sequential anastomosis under traditional CABG and OPCAB settings on postoperative myocardial injury, complication profiles, and long-term cardiac functional recovery needs to be rigorously investigated.

Therefore, this study aims to conduct a retrospective cohort analysis comparing early postoperative recovery metrics, complication rates, and cardiac hemodynamic recovery between on-pump CABG and off-pump CABG in patients who uniformly undergo the LIMA-LAD combined sequential no-touch. The findings are expected to provide valuable evidence-based guidance for optimizing surgical revascularization strategies and enhancing outcomes in high-risk coronary artery disease patients.

Methods

Research Object

This retrospective cohort study enrolled 240 patients who underwent LIMA-LAD bypass combined with sequential no-touch SVG anastomoses at The First Affiliated Hospital of Zhengzhou University, between June 2019 and December 2023. Based on different loop support strategies, study participants were categorized into two groups: the off-pump group (n = 179) and the on-pump group (n = 61). The study design was approved by the Ethics Review Board of The First Affiliated Hospital of Zhengzhou University (Approval No. L2022-Q083) and adhered to the principles outlined in the Declaration of Helsinki. Written informed consent was obtained from each participant before enrolling in this study.

Inclusion and Exclusion Criteria

Inclusion criteria for patient selection included (1) aged between 18 and 80 years, (2) confirmed diagnosis of three-vessel coronary artery disease, and (3) availability of complete clinical records. However, the exclusion criteria for patients were set as follows: (1) left ventricular ejection fraction (LVEF) <50%; (2) preoperative placement of an intra-aortic balloon pump (IABP); (3) malignancy with a life expectancy <1 year; (4) SVG diameter <1.2 mm as determined by Doppler ultrasound; (5) bilateral varicose saphenous veins or history of venous dissection; (6) concurrent ventricular septal perforation and ventricular aneurysm; (7) contraindication to dual antiplatelet therapy; (8) severe peripheral vascular disease; (9) known allergy to radiographic contrast agents; (10) requirement for emergency or salvage CABG; (11) active or uncontrolled systemic infectious disease; (12) active autoimmune disease; (13) known psychiatric or psychological disorders; (14) pregnancy or lactation; (15) significant bleeding tendency or coagulation disorders; and (16) recent use of anticoagulant therapy without the possibility of discontinuation.

Surgery Methods

The surgical interventions in both off-pump and on-pump groups were performed by the same group of experts and surgeons to minimize inter-procedure variability. The study cohort underwent the following surgical procedures.

The Off-Pump Group

All surgical interventions in the off-pump group were conducted on a beating heart.

(a) Preoperative evaluation and vascular acquisition

All patients underwent a detailed preoperative evaluation of both great saphenous veins (GSV) using Doppler ultrasound (HP-HX; Hewlett-Packard Company, Palo Alto, CA, USA) assessing diameter, patency, course, and anatomic features of the LIMA. The GSV was harvested strictly following the "no-touch" approach as detailed below:

• Sharp dissection to protect the adventitia: After a premarked skin incision, tissue scissors were used for sharp dissection. The target GSV section, along with its surrounding perivascular adipose tissue and adventitia, was freed as a whole vascular pedicle with approximately 0.5–0.8 cm of surrounding cushion tissue. Direct grasping or contact of the vein wall was avoided throughout the procedure.

• Branch treatment: Branch vessels were fastened with double titanium clips or ligated using a silk suture at least 3–5 mm from the main GSV trunk. Electrocoagulation near the main trunk to reduce thermal injury.

• Division and pretreatment: After complete mobilization, the vascular pedicle was double ligated at both proximal and distal ends and then divided. It was immediately immersed in autologous blood containing heparin (2500 U) and papaverine (30 mg), connected to an independent perfusion system (Stockert S3, Stockert GmbH, Freiburg, Germany), and perfused with low-pressure pulses of 25–35 mmHg to evaluate patency and leakage. The graft was preserved in heparin-papaverine saline for later use.

• Acquisition of left internal thoracic artery: Through a median sternotomy, the LIMA was dissected employing a combination of electric coagulation (20–30 W) and sharp dissection. The chest wall fascia within 1 cm of the artery was resected, and branches were secured using titanium clips, with the first intercostal branch ligated. After systemic heparinization (100 U/kg), 0.3% papaverine was sprayed on the surface of the vessel to prevent spasm. The artery was freed down to the bifurcation of the sixth rib.

(b) Cardiac fixation and anastomosis technique

• Exposure and fixation: The pericardium was cut and suspended to expose the target cardiac region. The Octopus coronary arteriostabilizer (TS2000, Medtronic Corporation, Minneapolis, MN, USA) was used to fix the target vessel area locally, and the apical positioning device was applied for better exposure. During the operation, the patient's body temperature and hemodynamic stability were carefully maintained to prevent ventricular fibrillation.

• Continuous anastomosis technique: All anastomoses were performed using 7-0 or 8-0 polypropylene continuous sutures.

• LIMA to LAD anastomosis: Firstly, an end-to-side anastomosis between the LIMA and LAD was performed using the "Parachute Technique". Two stitches were made at the "heel" and "toe" of the anastomotic site and suspended without tensioning the sutures, followed by continuous stitching along both sides, ensuring full-layer alignment and uniform needle distance (about 0.5–1 mm). The final knot was made at the midpoint. This technique ensured excellent visualization in the deep operative field.

• Sequential vein grafting: Sequential anastomosis was performed using the vein graft. A side-to-side "diamond-shaped" anastomosis (the long axis of the bridge vessel perpendicular to the coronary artery incision) was made between the graft and target vessel of the left circumflex system (such as the obtuse marginal branch), followed by an end-to-side anastomosis of the distal graft to the right coronary artery system (such as the posterior descending artery [PDA]). An intrashunt plug (Clearview®, Medtronic, Inc., Minneapolis, MN, USA) was routinely used to maintain distal myocardial perfusion and provide a bloodless operative field; meanwhile, continuous CO_2 spray (SA-6045, Nordson Micromedics, Westlake, OH, USA) was used to clear the anastomotic site area.

• Proximal anastomosis: After distal anastomosis, the proximal vein end was attached to the ascending aorta using a partial occluding clamp to preserve the aortic wall. After perforation, an end-to-side anastomosis was made using 6-0 polypropylene continuous sutures.

(c) Graft flow evaluation and chest closure

• Flow evaluation: After completing all anastomoses, the bridge vascular flow was immediately assessed using a transonic flowmeter (T206, Transonic System Inc., Ithaca, NY, USA). Adequate flow was defined as $\geq$20 mL/min with a pulsatility index $<$5. For those who failed to meet these criteria, the cause was immediately investigated and corrected.

• Postoperative treatment: Heparin was counteracted with fish sperm protein, and dual antiplatelet therapy was started. The lower extremity incision was closed in layers, and a pressure dressing was applied for 48–72 hours. Of the 179 off-pump CABG patients, none were converted to extracorporeal circulation during the operation.

Surgical Approaches Used in the On-Pump Group

All surgical procedures in this group were performed under CPB assistance with induced cardiac arrest by the same surgical team, ensuring technical comparability with the off-pump cohort.

(a) Establishment of cardiopulmonary bypass and myocardial protection

Following induction of general anesthesia, routine CPB was instituted via aortic and right atrial cannulation. Core body temperature was systematically reduced to 30 °C. After cross-clamping the ascending aorta, cold crystalloid cardioplegia (St. Thomas' solution) was administered through the aortic root to induce and maintain cardiac arrest and create a quiescent, bloodless surgical field for precise anastomoses.

(b) Vascular harvesting and anastomotic techniques

• Vessel procurement: The LIMA was harvested using a pedicled dissection technique, while the GSV was harvested employing the same standardized "no-touch" approach described in Section of "The Off-Pump Group", ensuring comparable graft quality between groups.

• Distal anastomoses: All distal anastomoses were performed during cardiac arrest.

• SVG anastomoses: The same anastomotic techniques and suture materials (7-0 polypropylene) were utilized in the off-pump group. For the GSV graft, a longitudinal arteriotomy was created in a target vessel of the left circumflex system, followed by a diamond-shaped side-to-side anastomosis (intermediate site). The distal terminus of this GSV conduit was subsequently anastomosed end-to-side to the posterior descending artery (PDA) (terminal anastomosis). The parachute technique was used to ensure precise vessel alignment and maintain anastomotic integrity.

• LIMA to LAD anastomosis: The pedicled LIMA was anastomosed end-to-side to the LAD artery using 7-0 polypropylene suture, aligning parallel to the LAD axis to optimize blood flow.

Proximal anastomosis and CPB discontinuation: Upon completion of all distal anastomoses, rewarming was initiated, and the aortic cross-clamp was released to restore coronary perfusion. Following spontaneous or defibrillated return of cardiac rhythm and hemodynamic stabilization, the ascending aorta was partially occluded to allow an end-to-side proximal anastomosis of the sequential GSV graft using 6-0 polypropylene suture. Complete air removal was performed before definitive aortic declamping, restoring global myocardial perfusion. Gradual weaning from CPB commenced once normothermia and hemodynamic stability were achieved.

(c) Postoperative management

• After achieving meticulous hemostasis, the CPB cannulas were removed. Pericardial and mediastinal drainage tubes were placed, and the chest was closed in layers.

Observation Indicators

Observational indicators assessed during this study were as follows:

(1) Baseline data: Baseline information for all patients was extracted from the electronic medical record system, which include age, sex, body mass index (BMI), body surface area (BSA), history of hypertension, diabetes mellitus, dyslipidemia, smoking history, chronic obstructive pulmonary disease (COPD), New York Heart Association (NYHA) functional classification, history of left main coronary artery disease, and left ventricular end diastolic diameter (LVEDD).

(2) Postoperative major adverse cardiovascular and cerebrovascular events (MACCE): Within one postoperative year, the incidence of myocardial infarction, all-cause mortality, stroke, and target vessel revascularization was recorded.

(3) Graft patency assessment: Postoperative graft patency was assessed at one year using multislice spiral computed tomography (MSCT) angiography, focusing on the LIMA-LAD graft and the sequential SVG. All 114 matched patients completed the 1-year MSCT follow-up, achieving a 100% compliance rate. The MSCT images were independently examined by three experienced cardiovascular imaging specialists who remained blind to the patients' group assignments. Bridge vessel patency was graded according to the FitzGibbon criteria: Grade A (excellent) and Grade B (acceptable) were considered patent, whereas Grade O (occluded)—defined as complete occlusion of the graft or anastomotic site—was categorized as non-patent [17]. Any discrepancies among reviewers were resolved through consensus discussion.

(4) Key indicators during hospitalization: These indicators included postoperative intensive care unit (ICU) stay duration (the time from the patient's transfer to the ICU until discharge from the ICU), duration of mechanical ventilation (the time interval between the first postoperative extubation attempt and complete cessation of mechanical ventilation), and total hospitalization duration (the total time from admission to discharge).

(5) Postoperative thoracic drainage volume: The total volume of thoracic drainage was assessed from the end of surgery until chest tube removal. Measurements were recorded using calibrated thoracic drainage bottles/bags, with fluid level documented immediately after each emptying.

(6) Postoperative blood transfusion volume: The total volume of all blood products administered from the end of surgery until hospital discharge, including packed red blood cells, plasma, cryoprecipitate, and related components, was documented. Data were retrieved from anesthesia records, blood transfusion logs, and nursing documentation.

(7) Hemodynamic parameters: Hemodynamic parameters were monitored at 24 hours postoperatively. Pulmonary artery wedge pressure (PAWP), cardiac output (CO), systemic vascular resistance index (SVRI), and mean arterial pressure (MAP) were measured using a Swan-Ganz catheter. The PAWP reported in this study, also known as pulmonary capillary wedge pressure (PCWP), carries the same physiological significance; hence, both terms are uniformly referred to as PAWP in this manuscript.

Heart rate (HR) was continuously recorded through pulse oximetry under stable resting conditions. Cardiac index (CI), stroke volume index (SVI), and left ventricular stroke work index (LVSWI) were derived as follows:

- CI (L/min/m^2) = CO / BSA
- SVI (mL/beat/m^2) = CI $\times$ 1000 / HR
- LVSWI (g·m/m^2) = SVI $\times$ (MAP – PAWP) $\times$ 0.0136

(8) Postoperative complications: Follow-up outcomes were obtained through outpatient visits, telephone interviews, and electronic health record review. Within the first postoperative month, the incidence of atrial fibrillation was recorded, while within 2 postoperative months, the incidence of acute kidney injury (AKI), sternal wound infection, and lower extremity venous territory infection was all documented.

Statistical Analysis

Statistical analysis was performed using SPSS version 26.0 (International Business Machines Corporation, Armonk, NY, USA). The Kolmogorov-Smirnov test was used to assess the normality of continuous variables. Data following a normal distribution were expressed as mean $\pm$ standard deviation ($\bar{x}$ $\pm$ s), with between-group comparisons performed using the independent samples *t*-test, and preoperative versus postoperative comparisons within-group

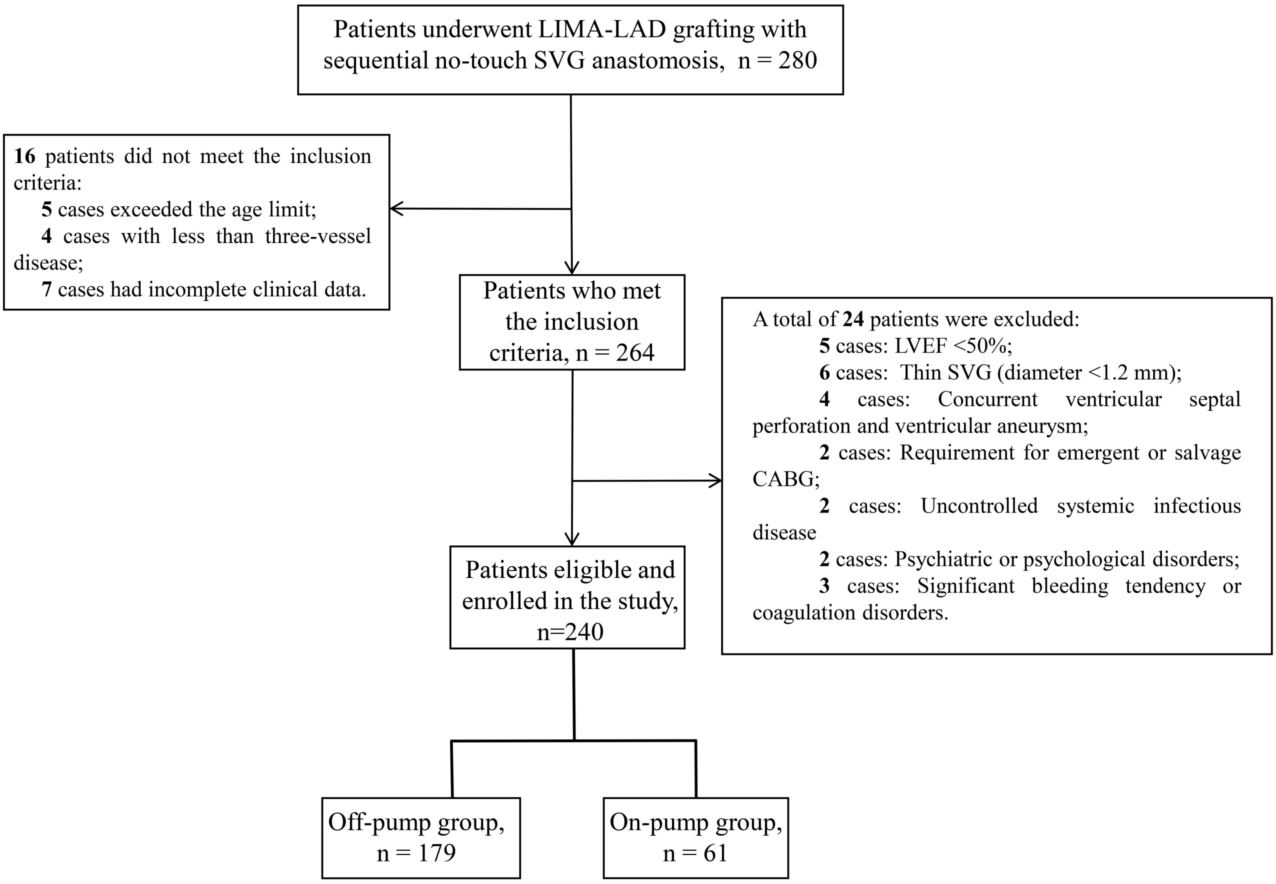

Fig. 1. A flow chart of study design and patient selection. LIMA, left internal mammary artery; LAD, left anterior descending artery; SVG, saphenous vein graft; LVEF, left ventricular ejection fraction.

conducted using the paired samples *t*-test. Non-normally distributed data were presented as median (Q1, Q3), with between-group comparisons performed using the Mann–Whitney U test and within-group comparisons using the Wilcoxon signed-rank test.

Categorical variables were presented as frequencies and percentages [n (%)], and differences were compared using the χ^2 test under the following conditions: (1) the Pearson χ^2 test was applied when the sample size (n) was $\geq$40 and all theoretical frequencies were $>$5; (2) Yates' corrected χ^2 test was used when n was $\geq$40 and at least one theoretical frequency was between 1 and 5; and (3) Fisher's exact test was employed when n was $<$40 or any theoretical frequency was $<$1.

Furthermore, a 1:1 propensity score matching (PSM) was performed using a logistic regression model to mitigate selection bias and reduce the impact of potential confounding variables in this observational study. The greedy nearest neighbor approach was applied, selecting patients in random order with a matching caliper set to 0.2 times the standard deviation of the natural logarithm of the propensity score.

The propensity score model treated the surgical method (on-pump versus off-pump) as the binary independent variable and incorporated the following covariates as predictors: age, sex, BMI, BSA, history of hypertension, diabetes mellitus, dyslipidemia, COPD, left main coronary disease, smoking status, NYHA functional class, and LVEDD. After matching, the balance between covariates was evaluated using the standardized mean difference (SMD), which was calculated as the difference in means divided by the pooled standard deviation. An SMD of less than 0.1 indicated adequate covariate balance. Reported *p*-values were two-sided, and statistical significance was achieved at a *p*-value $<$ 0.05.

This study utilized a retrospective design; therefore, no prospective sample size estimation was performed. A post-hoc power analysis was performed to assess the robustness of the results. For the MACCE, with the PSM sample size of 114 and significance level of α = 0.05, the study achieved 80% power to detect an absolute risk difference of at least 18%. For the secondary endpoint (atrial fibrillation), the statistical power was 85% for the observed difference (17.54% vs. 3.51%). This study established the incidence of 1-year MACCE as the primary endpoint. Analysis of secondary endpoints, including postoperative hemodynamic parameters, recovery indicators, and complications, was exploratory, aiming to provide a comprehensive clinical context for the primary endpoint and generate hypotheses for future research. Given the clinical heterogeneity and

Table 1. Comparison of baseline characteristics between the two groups before and after the PSM [$\bar{x} \pm$ s, n (%)].

Variable	Before PSM				After PSM			
	Off-pump group (n = 179)	On-pump group (n = 61)	*p*-value	SMD	Off-pump group (n = 57)	On-pump group (n = 57)	*p*-value	SMD
Age (years)	62.74 ± 8.40	61.46 ± 5.63	0.181	0.228	61.14 ± 5.98	61.39 ± 5.74	0.823	0.043
Male	130 (72.63)	45 (73.77)	0.862	0.026	43 (75.44)	41 (71.93)	0.671	0.078
BMI (kg/m^2)	23.50 ± 4.62	23.87 ± 3.73	0.577	0.098	23.82 ± 5.43	23.90 ± 3.73	0.927	0.022
BSA	1.81 ± 0.14	1.83 ± 0.16	0.341	0.128	1.81 ± 0.14	1.82 ± 0.16	0.910	0.020
Hypertension	66 (36.87)	21 (34.43)	0.732	0.051	20 (35.09)	21 (36.84)	0.845	0.036
Diabetes mellitus	47 (26.26)	15 (24.59)	0.797	0.039	17 (29.82)	15 (26.32)	0.677	0.080
Dyslipidemia	71 (39.66)	25 (40.98)	0.856	0.027	21 (36.84)	22 (38.60)	0.847	0.036
COPD	8 (4.47)	3 (4.92)	1.000	0.021	2 (3.51)	3 (5.26)	1.000	0.079
Left main disease	57 (31.84)	18 (29.51)	0.734	0.051	18 (31.58)	18 (31.58)	1.000	0.000
Smoking	70 (39.11)	23 (37.70)	0.846	0.029	21 (36.84)	22 (38.60)	0.847	0.036
NYHA III–IV	67 (37.43)	26 (42.62)	0.472	0.105	21 (36.84)	22 (38.60)	0.847	0.036
LVEDD (mm)	48.63 ± 5.78	47.84 ± 3.29	0.189	0.242	47.82 ± 5.79	47.95 ± 3.37	0.890	0.036

Note: PSM, propensity score matching; BMI, body mass index; BSA, body surface area; COPD, chronic obstructive pulmonary disease; NYHA, New York Heart Association; LVEDD, left ventricular end diastolic diameter; SMD, standardized mean difference.

descriptive purpose of these secondary endpoints, adjustment of the family-wise error rate was not applied.

Results

Clinical Baseline Characteristics Across the Study Cohort

This retrospective cohort study included 240 patients who underwent LIMA to left anterior descending artery bypass surgery combined with sequential no-touch grafting at our hospital. Based on clinical records, participants were divided into two groups according to the surgical support strategies: the non-extracorporeal circulation group (off-pump group, n = 179) and the extracorporeal circulation group (on-pump group, n = 61). The specific patient selection process is shown in Fig. 1.

Before PSM, no statistically significant differences were observed in the overall clinical characteristics between the two groups ($p > 0.05$). However, the SMD values indicated baseline imbalances in age, BSA, NYHA functional class, and LVEDD (SMD >0.1, Table 1). Following 1:1 PSM, 57 matched pairs were obtained. After matching, baseline characteristics were balanced between the two groups, with no significant intergroup differences observed across any parameters ($p > 0.05$), and all SMD values were below 0.1 (Table 1).

One-Year Postoperative MACCE and One-Year Postoperative Graft Patency Rate

After PSM, no significant differences were found between the off-pump and on-pump groups in the incidence of MACCE during the 1-year follow-up, including all-cause mortality, myocardial infarction, stroke, and target vessel revascularization ($p > 0.05$, Table 2). Similarly, there were no significant differences between the two groups in the one-year patency rates of the LIMA-LAD graft or the sequential SVG bridge ($p > 0.05$, Table 3).

Early Postoperative Outcomes

After PSM, postoperative outcomes revealed that the off-pump group had shorter postoperative ICU stays, reduced mechanical ventilation duration, lower thoracic drainage volume, and reduced blood transfusion requirements compared to the on-pump group ($p < 0.001$). However, there was no significant difference in total hospitalization duration between the two groups ($p > 0.05$, Table 4).

Comparison of Hemodynamic Parameters Between the Two Groups

Following PSM, no significant postoperative differences were found between the two groups in hemodynamic parameters, including CI, PAWP, LVSWI, SVI, MAP and SVRI ($p > 0.05$, Table 5).

At 24 hours postoperatively, within-group analyses revealed significant improvements in all measured parameters in the off-pump group, and in CI, PAWP, LVSWI, and SVRI in the on-pump group compared to their respective preoperative values ($p < 0.05$). Between-group comparisons at this point demonstrated that the off-pump group had better CI, PAWP, LVSWI, SVI, and SVRI values than the on-pump group ($p < 0.05$, Table 5).

Comparison of Postoperative Complications Between the Two Groups

After PSM, the incidence of atrial fibrillation was significantly lower in the off-pump group than in the on-pump group one month postoperatively ($p < 0.05$). However, no significant differences were observed between the two groups in the rates of AKI, sternal wound infection, or lower extremity venous territory infection two months postoperatively ($p > 0.05$, Table 6).

Table 2. Comparison of one-year postoperative MACCE between the two groups after PSM [n (%)].

Group	All-cause mortality	Myocardial infarction	Stroke	Target vessel revascularization
Off-pump group (n = 57)	1 (1.75)	2 (3.51)	1 (1.75)	4 (7.02)
On-pump group (n = 57)	2 (3.51)	5 (8.77)	2 (3.51)	7 (12.28)
χ^2	*	*	*	0.906
p-value	1.000	0.438	1.000	0.341

Note: MACCE, major adverse cardiovascular and cerebrovascular events. *Fisher's exact test.

Table 3. Comparison of one-year postoperative graft patency between the two groups after PSM [n (%)].

Group	LIMA-LAD graft patency	Sequential SVG graft patency
Off-pump group (n = 57)	56 (98.25)	51 (89.47)
On-pump group (n = 57)	55 (96.49)	52 (91.23)
χ^2 (Yates)	0.001	0.101
p-value	1.000	0.751

Note: SVG, saphenous vein graft.

Discussion

The major finding of this study is that among patients undergoing standardized LIMA-LAD anastomoses with sequential no-touch SVGs, there were no significant differences between ONCAB and OPCAB strategies in the incidence of one-year MACCE or graft patency rates. This result holds substantial clinical significance, demonstrating that OPCAB can provide long-term efficacy comparable to ONCAB when performed using standardized, advanced surgical techniques by experienced surgical teams. These findings align with recent high-quality studies and meta-analyses of randomized trials, which collectively indicate that modern surgical practices yield comparable long-term outcomes for both OPCAB and ONCAB [18–20].

Early studies may have reported inconsistent results, likely impacted by the surgical learning curve and technical disparities. The consistency of our findings can be due to several critical factors. First, all patients underwent an identical revascularization strategy, which minimized confounding biases arising from variations in target vessel selection and grafting approaches, enabling a more precise assessment of the intrinsic effects of the two perfusion techniques. Second, using the no-touch GSV harvesting technique likely played a pivotal role in ensuring long-term graft patency. By preserving the 'biological scaffold' function of the venous adventitia, this method significantly reduced risks of vasospasm and anastomotic distortion, thereby providing an optimal technical foundation for sequential anastomoses [21]. This vascular protective advantage may effectively compensate for potential technical challenges associated with performing anastomoses on a static heart without cardiopulmonary bypass. Finally, extensive expertise from the surgical team was a crucial factor. At our institution, approximately 75% of CABG procedures are conducted using off-pump approaches, indicating the proficiency of the OPCAB method. Such proficiency ensures anastomotic precision and long-term patency rates comparable to those achieved with ONCAB, explaining why our study successfully replicated the results observed in randomized controlled trials conducted at expert centers [22]. In summary, when performed by an experienced surgical team adhering to standardized revascularization protocols, particularly incorporating no-touch vein harvesting techniques, off-pump CABG can achieve comparable 1-year clinical and graft patency outcomes to on-pump CABG.

This study compared clinical outcomes between on-pump and off-pump strategies for LIMA-LAD grafting combined with sequential no-touch GSV anastomosis. The off-pump group showed substantially reduced ICU stays, shorter mechanical ventilation time, lower chest tube drainage volume, and decreased transfusion requirements. Consistent with our results, recent studies comparing CABG with and without extracorporeal circulation have found that OPCAB may offer potential advantages over on-pump CABG in terms of early postoperative clinical outcomes for patients [6,23]. These advantages primarily stem from avoiding systemic injury associated with CPB. Contact between blood and artificial surfaces during CPB activates the complement system and releases pro-inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α) resulting in pulmonary edema, impaired gas exchange, and prolonged mechanical ventilation requirements [24]. Off-pump surgery circumvents this inflammatory response, resulting in significantly lower levels of inflammatory markers and accelerated recovery of respiratory function [25]. Furthermore, CPB-related heparinization, platelet depletion, and hyperfibrinolysis predispose patients to coagulopathy [26]. By maintaining coagulation integrity, the off-pump approach reduces postoperative bleeding and transfusion needs, thereby minimizing the risk of infection and blood transfusion-associated morbidity and mortality [6,27].

This study revealed no significant preoperative differences between the two groups regarding hemodynamic parameters (CI, PAWP, LVSWI, SVI, MAP, SVRI), indicating comparable baseline characteristics. The first 24 hours after surgery represent a critical window period [28], during

Table 4. Comparison of early postoperative outcomes between the two groups after PSM [$\bar{x} \pm s$].

Group	ICU duration (h)	Duration of mechanical ventilation (h)	Length of stay (d)	Thoracic drainage volume (mL)	Blood transfusion volume (units)
Off-pump group (n = 57)	42.31 ± 10.98	13.83 ± 3.76	25.24 ± 7.28	244.79 ± 61.50	1.90 ± 0.48
On-pump group (n = 57)	49.54 ± 10.45	20.60 ± 3.27	27.38 ± 5.81	284.12 ± 60.16	3.29 ± 0.38
t	3.601	10.247	1.735	3.452	17.204
p-value	<0.001	<0.001	0.086	<0.001	<0.001

ICU, intensive care unit.

Table 5. Comparison of hemodynamic indicators between the two groups after PSM [$\bar{x} \pm s$, Median (Q1, Q3)].

Group	CI		PAWP		LVSWI		SVI		MAP		SVRI	
Group	Before the surgery	After the surgery	Before the surgery	After the surgery	Before the surgery	After the surgery	Before the surgery	After the surgery	Before the surgery	After the surgery	Before the surgery	After the surgery
Off-pump group (n = 57)	1.97 ± 0.37	2.55 ± 0.48**	12.00 (10.00, 14.00)	11.00 (9.00, 12.00)*	28.10 ± 6.30	35.72 ± 8.14**	26.37 ± 6.00	31.35 ± 5.33**	78.60 ± 10.33	74.14 ± 8.44*	1960.89 ± 79.55	1856.93 ± 76.56**
On-pump group (n = 57)	1.97 ± 0.22	2.29 ± 0.34**	13.00 (11.00, 15.00)	14.00 (12.50, 17.00)*	28.10 ± 5.85	30.41 ± 5.32*	26.19 ± 6.78	28.32 ± 4.27	80.96 ± 9.31	76.74 ± 6.35*	1964.53 ± 74.00	2269.88 ± 78.34**
t/Z	0.031	3.404	1.506	6.851	0.005	4.125	0.146	3.356	1.285	1.856	0.252	28.463
p-value	0.975	<0.001	0.132	<0.001	0.996	<0.001	0.884	0.001	0.201	0.066	0.801	<0.001

Note: CI, cardiac index; PAWP, pulmonary artery wedge pressure; LVSWI, left ventricular stroke work index; SVI, stroke volume index; MAP, mean arterial pressure; SVRI, systemic vascular resistance index. Compared with the same group before surgery, *$p < 0.05$, **$p < 0.001$.

Table 6. Comparison of postoperative complications between the two groups after PSM [n (%)].

Group	Atrial fibrillation	AKI	Sternal wound infection	Lower extremity venous territory infection
Off-pump group (n = 57)	2 (3.51)	4 (7.02)	1 (1.75)	2 (3.51)
On-pump group (n = 57)	10 (17.54)	7 (12.28)	2 (3.51)	3 (5.26)
χ^2	5.961	0.906	Fisher	Fisher
p-value	0.015	0.341	1.000	1.000

AKI, acute kidney injury.

which patients recover from the effects of cardiopulmonary bypass and anesthesia, as the myocardium and systemic circulation undergo crucial adjustment to re-establish functional equilibrium. Hemodynamic parameters during this period provide sensitive measures of myocardial protection efficacy, graft patency, and the initial cardiac response to surgical trauma. Even minor technical differences may become significantly amplified and clinically evident within this vulnerable postoperative window [29,30].

In this study cohort, patients who received off-pump coronary artery bypass grafting demonstrated considerable hemodynamic advantages 24 hours after the procedure, including improved cardiac function (evidenced by higher CI, SVI, and LVSWI) and enhanced vasculature performance as indicated by lower PAWP and SVRI, compared to those managed with on-pump techniques. This comprehensive improvement carries significant clinical implications. The substantial increase in CI, SVI, and LVSWI signifies more efficient early postoperative contractile and pumping efficiency [31,32]. Notably, the significant reduction in PAWP indicates optimized left ventricular filling pressures and decreased pulmonary hydrostatic pressure, which is crucial for preventing postoperative pulmonary edema and sustaining adequate gas exchange [33]. Additionally, the observed decrease in SVRI reflects improved peripheral vasodilation capacity and reduced cardiac afterload [34]. This hemodynamic state facilitates more effective ventriculo-arterial coupling, thereby enhancing cardiac work efficiency and systemic tissue perfusion [35].

These synergistic hemodynamic advantages can be directly attributed to the fact that OPCAB avoids global myocardial ischemia-reperfusion injury, maintains continuous coronary perfusion during anastomoses, and mitigates myocardial stunning, thereby enhancing postoperative CI and LVSWI [36]. Conversely, CPB triggers a systemic inflammatory response that increases pulmonary vascular permeability, resulting in interstitial edema and elevated left ventricular preload, manifested as higher PAWP [37]. Furthermore, the increased SVRI found in the on-pump group likely results from microvascular thrombosis, inflammatory vasospasm (primarily mediated by TNF-α and IL-6), and hemoconcentration, all of which contribute to higher afterload and impaired ventricular-vascular coupling [38]. In contrast, the reduced SVRI found in the off-pump group reflects preserved endothelial integrity and better peripheral vasodilatory capability than the on-pump group [39].

Despite earlier reports from the Randomized On/Off Bypass (ROOBY) trial indicating lower patency rates for OPCAB, our study demonstrated no significant differences between the two groups in 1-year patency rates for either LIMA-LAD or sequential SVGs [40]. The methodological differences between these results likely explain this disparity and bolster the validity of our non-inferiority conclusion. Foremost among these is the fundamental difference in grafting technique; unlike the ROOBY trial, which predominantly employed conventional harvesting methods prone to mechanical stretching and endothelial injury.

In contrast, our study exclusively employed the ‘no-touch’ technique, in which the saphenous vein is harvested with its surrounding tissue pedicle, preserving the vasa vasorum and minimizing mechanical trauma. This technique has been robustly associated with superior short- and long-term patency rates, comparable to those of the left internal mammary artery, as demonstrated in several landmark studies [21,41]. Implementing this technically superior harvesting method in our off-pump cohort may have mitigated a key contributor to graft failure in earlier studies. Another key distinction lies in the level of surgical expertise. The learning curve and operator expertise in off-pump CABG are crucial confounding factors. The ROOBY trial was conducted across multiple Veterans Affairs centers, involving surgeons with varying levels of off-pump experience, introducing potential differences that may have impacted the observed outcomes.

Our study, however, was performed at a high-volume cardiac surgery center where all procedures were conducted by a small team of dedicated surgeons with extensive experience and had long surpassed the learning curve for complex OPCAB procedures, including sequential anastomosis. Therefore, the excellent and comparable graft patency outcomes found in our study are attributed to the combination of an advanced vein harvesting technique (no-touch) and a high level of technical expertise in off-pump procedures. Overall, these observations highlight that when conducted by experienced surgeons using modern approaches, off-pump CABG can yield a graft patency rate comparable to that achieved with the on-pump method.

In terms of postoperative complications, we observed that patients who received OPCAB exhibited a significantly lower incidence of postoperative atrial fibrillation than those who underwent ONCAB. This finding aligns with the results from large-scale observational studies and meta-analyses, further supporting the potential of OPCAB to mitigate this common complication [42,43]. The mechanisms underlying this protective role are likely multifaceted. The application of CPB in ONCAB induces a substantial systemic inflammatory response, triggering the release of pro-inflammatory cytokines, including TNF-α and IL-6, which consequently promote atrial electrophysiological instability [44]. Additionally, CPB can compromise atrial myocardial perfusion, resulting in localized ischemia. Conversely, OPCAB obviates the need for aortic cannulation and cardiac arrest, maintaining intrinsic cardiac contraction during anastomoses. This approach potentially minimizes mechanical strain on atrial tissue, reduces pericardial inflammation, and helps preserve autonomic balance, all collectively contribute to a reduced risk of postoperative atrial fibrillation [6,45].

From a clinical perspective, reducing atrial fibrillation incidence has several advantages: shorter ICU stays, reduced total hospital length of stay, lower perioperative complications such as stroke, and decreased healthcare costs. Consequently, for patients with a high-risk of postoperative atrial fibrillation, OPCAB presents a more compelling surgical strategy.

No significant differences were observed between the groups in infectious complication rates. Existing literature indicates that although the "no-touch" technique substantially improves graft patency, its technical requirement to harvest venous tissue pedicled with surrounding adipose tissue expands the dissection areas and can damage lymphatic vessels and cutaneous nerves. This increases the risk of lower extremity pain, numbness, edema, and wound exudation [46,47]. Patients receiving on-pump surgery are generally more prone to systemic infections; however, both groups in our study experienced significant local surgical trauma due to the "no-touch" GSV harvesting technique. This increased trauma elevates the risk of local wound infections, effectively counterbalancing the on-pump group's higher systemic infection risk. Consequently, overall infection rates remained comparable between the two approaches. Anatomically informed technical modifications to surgical strategy have proven valuable in addressing these complications. Adopting interrupted skin bridges combined with closed drainage helps preserve lymphatic pathways and eliminates dead space, reducing wound-related complications by about 30% [48].

Our findings revealed no statistically significant difference in the incidence of AKI between the two groups. Several potential factors may be attributed to this finding. CPB is a well-known contributor to AKI risk through mechanisms such as hemolysis, renal hypoperfusion, and inflammatory responses [49]. In contrast, intraoperative cardiac manipulation in OPCAB may induce transient hypotension [50]. As a result, the overall AKI rates between the two approaches are comparable. Additionally, contemporary cardiac surgery has led to the widespread adoption of kidney-protective strategies—including goal-directed perfusion management and restricted crystalloid administration—effectively reducing CPB-associated renal injury. These measures have significantly minimized differences in renal outcome between CPB and OPCAB approaches [51,52]. In summary, this study provides a comprehensive assessment of postoperative complication profiles for on-pump and off-pump CABG, elucidating their underlying pathophysiological mechanisms. It also highlights the significance of technical refinements, such as interrupted skin bridges with closed drainage and optimized perioperative management, including renal protective strategies, in improving patient outcomes.

Despite several promising outcomes, we acknowledge certain limitations to this study. First, its retrospective observational design renders it inherently susceptible to selection bias and unmeasured confounding. Data on the exact number of target vessels or anastomotic sites and quantitative parameters of surgeon experience were not systematically collected and analyzed, potentially introducing unmeasured confounding bias. The decision to conduct either on-pump or off-pump CABG was made entirely at the discretion of the operating surgeon and may have been influenced by factors not fully captured in the database (e.g., individual surgeon preferences or intraoperative assessment of aortic quality). Although propensity score matching effectively controls for measured covariates, it cannot eliminate the impact of unmeasured confounders. Consequently, our findings should be interpreted as associations rather than definitive causal inferences.

Second, extensive sensitivity analyses, like varying the caliper widths in the PSM, were not performed to further validate the robustness of the findings. This limitation stems from practical constraints: widening the caliper could compromise the precision of matching, whereas narrowing it might exclude too many cases, reduce the effective sample size, and lower statistical power. Nevertheless, we ensured matching quality by thoroughly reporting post-match SMD; all covariates demonstrated SMD below 0.1, indicating satisfactory baseline balance across measured parameters.

Third, although our cohort size sufficed to detect differences in primary endpoints (MACCE), the single-center design of the study limited its statistical power for assessing rare postoperative complications (e.g., deep sternal wound infections). However, post-hoc power analysis provides crucial insights for interpreting our findings: the study demonstrated sufficient statistical power (85%) to detect a significant reduction in postoperative atrial fibrillation among off-pump CABG patients. Both groups showed comparable MACCE incidence, below the predicted clinically meaningful threshold of an 18% difference, effectively excluding any major adverse impact of the off-pump CABG approach. Though the study may be underpowered to detect small differences, the consistent trend of outcomes across all measured components suggests that undetected variations are unlikely to be clinically crucial.

Fourth, while a one-year follow-up is standard for evaluating early graft patency and perioperative outcomes, it does not capture the long-term durability of saphenous vein grafts, which are well-documented to deteriorate progressively over time. Although "off-pump" techniques have been associated with improved long-term patency, a definitive conclusion regarding the observed benefits (particularly for sequential saphenous vein conduits) requires extended follow-up. Thus, any findings of equivalence between the two surgical approaches regarding infrequent long-term events should be interpreted cautiously.

Finally, patients with significantly impaired left ventricular function (LVEF <50%) were not included in this study. Although this restriction helped establish a more homogeneous cohort and isolate the effect of perfusion strategy by minimizing heart failure-related confounding, it consequently limits the generalizability of our results. These results are most applicable to patients with preserved systolic function. Given that off-pump strategies are often preferred for high-risk patients with poor cardiac performance to avoid the potential deleterious effects of cardiopulmonary bypass, the optimal use of this hybrid technique in those subgroups remains undetermined and warrants further investigation. We plan to address these challenges through larger multicenter prospective randomized controlled trials with prolonged postoperative monitoring (3-, 5-, 10-year intervals) in subsequent research.

Conclusions

This study demonstrates that off-pump LIMA to LAD CABG combined with no-touch saphenous vein sequential anastomosis confers significant advantages over the on-pump approach in key early recovery outcomes, including reduced ICU utilization, accelerated respiratory recovery, decreased blood loss, and optimized postoperative hemodynamics. Its lower incidence of atrial fibrillation further corroborates its safety profile. Notably, the off-pump approach yields comparable long-term outcomes with no substantial differences in one-year graft patency rates or MACCE incidence compared with the on-pump method.

Availability of Data and Materials

The data used and analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

XZ and JX designed the research study and wrote the first draft. ZKZ and QC performed the research. YKZ and CH analyzed the data. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study design was approved by the Ethics Review Board of The First Affiliated Hospital of Zhengzhou University (Approval No. L2022-Q083) and adhered to the principles outlined in the Declaration of Helsinki. Written informed consent was obtained from each participant before enrolling in this study.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Gáspár R, Halmi D, Demján V, Berkecz R, Pipicz M, Csont T. Kynurenine Pathway Metabolites as Potential Clinical Biomarkers in Coronary Artery Disease. Frontiers in Immunology. 2022; 12: 768560. https://doi.org/10.3389/fimmu.2021.768560.

[2] Chen L, He Y, Wang Y, Liu S, Li Q, *et al*. Association of Angina, Myocardial Infarction and Atrial Fibrillation-A Bidirectional Mendelian Randomization Study. British Journal of Hospital Medicine. 2024; 85: 1–13. https://doi.org/10.12968/hmed.2024.0137.

[3] Katta N, Loethen T, Lavie CJ, Alpert MA. Obesity and Coronary Heart Disease: Epidemiology, Pathology, and Coronary Artery Imaging. Current Problems in Cardiology. 2021; 46: 100655. https://doi.org/10.1016/j.cpcardiol.2020.100655.

[4] Wang G, Li F, Hou X. Complementary and alternative therapies for stable angina pectoris of coronary heart disease: A protocol for systematic review and network meta-analysis. Medicine. 2022; 101: e28850. https://doi.org/10.1097/MD.0000000000028850.

[5] Giacinto O, Satriano U, Nenna A, Spadaccio C, Lusini M, Mastroianni C, *et al*. Inflammatory Response and Endothelial Dysfunction Following Cardiopulmonary Bypass: Pathophysiology and Pharmacological Targets. Recent Patents on Inflammation & Allergy Drug Discovery. 2019; 13: 158–173. https://doi.org/10.2174/1872213X13666190724112644.

[6] Wang C, Jiang Y, Song Y, Wang Q, Tian R, Wang D, *et al*. Off-pump or on-pump coronary artery bypass at 30 days: A propensity matched analysis. Frontiers in Cardiovascular Medicine. 2022; 9: 965648. https://doi.org/10.3389/fcvm.2022.965648.

[7] Guan Z, Guan X, Gu K, Lin X, Lin J, Zhou W, *et al*. Short-term outcomes of on- vs off-pump coronary artery bypass grafting in patients with left ventricular dysfunction: a systematic review and meta-analysis. Journal of Cardiothoracic Surgery. 2020; 15: 84. https://doi.org/10.1186/s13019-020-01115-0.

[8] Verma S, Fedak PWM, Weisel RD, Szmitko PE, Badiwala MV, Bonneau D, *et al*. Off-pump coronary artery bypass surgery: fundamentals for the clinical cardiologist. Circulation. 2004; 109: 1206–1211. https://doi.org/10.1161/01.CIR.0000120292.65143.F5.

[9] Rodgers-Fischl PM, Makdisi G. Internal Thoracic Artery and Vascular Adaptations. The Annals of Thoracic Surgery. 2022; 113: 695. https://doi.org/10.1016/j.athoracsur.2021.05.032.

[10] Harky A, Sankaranarayanan V, Kong QG. Internal mammary artery: the primary conduit for surgical revascularization. Coronary Artery Disease. 2021; 32: 64–72. https://doi.org/10.1097/MCA.0000000000000895.

[11] Jiang Q, Yang Y, Sun H, Tang Y, Lv F, Hu S. Stable Hemodynamics

within “No-Touch” Saphenous Vein Graft. Annals of Thoracic and Cardiovascular Surgery. 2020; 26: 88–94. https://doi.org/10.5761/atcs.oa.19-00156.

[12] Tian M, Wang X, Sun H, Feng W, Song Y, Lu F, *et al*. No-Touch Versus Conventional Vein Harvesting Techniques at 12 Months After Coronary Artery Bypass Grafting Surgery: Multicenter Randomized, Controlled Trial. Circulation. 2021; 144: 1120–1129. https://doi.org/10.1161/CIRCULATIONAHA.121.055525.

[13] Yuan SM, Jing H. A reappraisal of saphenous vein grafting. Annals of Saudi Medicine. 2011; 31: 62–71. https://doi.org/10.4103/0256-4947.75781.

[14] Park SJ, Kim HJ, Kim JB, Jung SH, Choo SJ, Lee JW, *et al*. Sequential Versus Individual Saphenous Vein Grafting During Coronary Arterial Bypass Surgery. The Annals of Thoracic Surgery. 2020; 109: 1165–1173. https://doi.org/10.1016/j.athoracsur.2019.07.094.

[15] Zhao TY, Bu JQ, Gu JJ, Liu Y, Zhang WL, Chen ZY. The Short-Term Patency Rate of a Saphenous Vein Bridge Using the No-Touch Technique in off-Pump Coronary Artery Bypass Grafting in Vein Harvesting. International Journal of General Medicine. 2021; 14: 2281–2288. https://doi.org/10.2147/IJGM.S311249.

[16] Hou X, Zhang K, Liu T, Li Y, Zhao Y, Song B, *et al*. No-Touch Sequential Saphenous Venous Harvesting Technique in Off-Pump Bypass Surgery: A Retrospective Study. Frontiers in Cardiovascular Medicine. 2022; 8: 804739. https://doi.org/10.3389/fcvm.2021.804739.

[17] FitzGibbon GM, Burton JR, Leach AJ. Coronary bypass graft fate: angiographic grading of 1400 consecutive grafts early after operation and of 1132 after one year. Circulation. 1978; 57: 1070–1074. https://doi.org/10.1161/01.cir.57.6.1070.

[18] Sajja LR, Sarkar K, Mannam G, Kodali VKK, Padmanabhan C, Peter S, *et al*. One-year outcomes of off- and on-pump coronary artery bypass grafting: PROMOTE patency trial. Indian Journal of Thoracic and Cardiovascular Surgery. 2020; 36: 469–475. https://doi.org/10.1007/s12055-020-00940-1.

[19] Forouzannia SM, Forouzannia SK, Yarahmadi P, Alirezaei M, Shafiee A, Anari NY, *et al*. Early and mid-term outcomes of off-pump versus on-pump coronary artery bypass surgery in patients with triple-vessel coronary artery disease: a randomized controlled trial. Journal of Cardiothoracic Surgery. 2023; 18: 140. https://doi.org/10.1186/s13019-023-02258-6.

[20] Sajja LR, Sarkar K, Mannam G, Kodali VKK, Padmanabhan C, Peter S, *et al*. Graft patency at 3 months after off- and on-pump coronary bypass surgery: a randomized trial. Indian Journal of Thoracic and Cardiovascular Surgery. 2020; 36: 93–104. https://doi.org/10.1007/s12055-019-00869-0.

[21] Arbeus M, Souza D, Geijer H, Lidén M, Pinheiro B, Bodin L, *et al*. Five-year patency for the no-touch saphenous vein and the left internal thoracic artery in on- and off-pump coronary artery bypass grafting. Journal of Cardiac Surgery. 2021; 36: 3702–3708. https://doi.org/10.1111/jocs.15853.

[22] Gurram A, Krishna N, Vasudevan A, Baquero LA, Jayant A, Varma PK. Female Gender is not a Risk Factor for Early Mortality after Coronary Artery Bypass Grafting. Annals of Cardiac Anaesthesia. 2019; 22: 187–193. https://doi.org/10.4103/aca.ACA_27_18.

[23] Zhang P, Wang L, Zhai K, Huang J, Wang W, Ma Q, *et al*. Off-pump versus on-pump redo coronary artery bypass grafting: a systematic review and meta-analysis. Perfusion. 2021; 36: 724–736. https://doi.org/10.1177/0267659120960310.

[24] Hatami S, Hefler J, Freed DH. Inflammation and Oxidative Stress in the Context of Extracorporeal Cardiac and Pulmonary Support. Frontiers in Immunology. 2022; 13: 831930. https://doi.org/10.3389/fimmu.2022.831930.

[25] Mirhafez SR, Khadem SH, Sahebkar A, Movahedi A, Rahsepar AA, Mirzaie A, *et al*. Comparative effects of on-pump versus off-pump coronary artery bypass grafting surgery on serum cytokine and chemokine levels. IUBMB Life. 2021; 73: 1423–1431. https://doi.org/10.1002/iub.2566.

[26] Korte J, Lauwigi T, Herzog L, Theißen A, Suchorski K, Strudthoff LJ, *et al*. Prediction of Thrombus Formation within an Oxygenator via Bioimpedance Analysis. Biosensors. 2024; 14: 511. https://doi.org/10.3390/bios14100511.

[27] Lee SH, Kim JE, Lee JH, Jung JS, Son HS, Kim HJ. Perioperative Red Blood Cell Transfusion and Long-Term Mortality in Coronary Artery Bypass Grafting: On-Pump and Off-Pump Analysis. Journal of Clinical Medicine. 2025; 14: 2662. https://doi.org/10.3390/jcm14082662.

[28] St André AC, DelRossi A. Hemodynamic management of patients in the first 24 hours after cardiac surgery. Critical Care Medicine. 2005; 33: 2082–2093. https://doi.org/10.1097/01.ccm.0000178355.96817.81.

[29] Shen X, Tao H, Chen W, Sun J, Jin R, Zhang W, *et al*. Perioperative blood pressure variability as a risk factor for postoperative delirium in the patients receiving cardiac surgery. BMC Anesthesiology. 2024; 24: 424. https://doi.org/10.1186/s12871-024-02817-x.

[30] Bulow NMH, Colpo E, Pereira RP, Correa EFM, Waczuk EP, Duarte MF, *et al*. Dexmedetomidine decreases the inflammatory response to myocardial surgery under mini-cardiopulmonary bypass. Brazilian Journal of Medical and Biological Research. 2016; 49: e4646. https://doi.org/10.1590/1414-431X20154646.

[31] Sato K, Hoe LS, Chan J, Obonyo NG, Wildi K, Heinsar S, *et al*. Echocardiographic surrogate of left ventricular stroke work in a model of brain stem death donors. European Journal of Clinical Investigation. 2024; 54: e14259. https://doi.org/10.1111/eci.14259.

[32] Furrer K, Bettex D, Horisberger T, Inci I, Nagaraj NG, Morselli HT, *et al*. Fluid management of cardiopulmonary bypass during pulmonary endarterectomy for CTEPH patients impacts perioperative outcome. JHLT Open. 2025; 9: 100253. https://doi.org/10.1016/j.jhlto.2025.100253.

[33] Mayeux JD, Pan IZ, Dechand J, Jacobs JA, Jones TL, McKellar SH, *et al*. Management of Pulmonary Arterial Hypertension. Current Cardiovascular Risk Reports. 2021; 15: 2. https://doi.org/10.1007/s12170-020-00663-3.

[34] Lopaschuk GD, Verma S. Mechanisms of Cardiovascular Benefits of Sodium Glucose Co-Transporter 2 (SGLT2) Inhibitors: A State-of-the-Art Review. JACC. Basic to Translational Science. 2020; 5: 632–644. https://doi.org/10.1016/j.jacbts.2020.02.004.

[35] Patsalis N, Kreutz J, Chatzis G, Syntila S, Griewing S, Pirlet-Grant C, *et al*. Renal Protection and Hemodynamic Improvement by Impella® Microaxial Pump in Patients with Cardiogenic Shock. Journal of Clinical Medicine. 2022; 11: 6817. https://doi.org/10.3390/jcm11226817.

[36] Al Jaaly E, Zakkar M, Fiorentino F, Angelini GD. Pulmonary Protection Strategies in Cardiac Surgery: Are We Making Any Progress? Oxidative Medicine and Cellular Longevity. 2015; 2015: 416235. https://doi.org/10.1155/2015/416235.

[37] Sandeep B, Xiao Z, Zhao F, Feng Q, Gao K. Role of Platelets in Acute Lung Injury After Extracorporeal Circulation in Cardiac Surgery Patients: A Systemic Review. Current Problems in Cardiology. 2022; 47: 101088. https://doi.org/10.1016/j.cpcardiol.2021.101088.

[38] Umeki A, Yamamoto T. Analysis of systemic vascular resistance after cardiac surgery: a retrospective cohort study. Journal of Thoracic Disease. 2022; 14: 4341–4351. https://doi.org/10.21037/jtd-22-325.

[39] Vedin J, Jensen U, Ericsson A, Bitkover C, Samuelsson S, Bredin F, *et al*. Cardiovascular function during the first 24 hours after off pump coronary artery bypass grafting–a prospective, randomized study. Interactive Cardiovascular and Thoracic Surgery. 2003; 2: 489–494. https://doi.org/10.1016/S1569-9293(03)00119-1.

[40] Shroyer AL, Grover FL, Hattler B, Collins JF, McDonald GO, Kozora E, *et al*. On-pump versus off-pump coronary-artery bypass surgery. The New England Journal of Medicine. 2009; 361: 1827–1837. https://doi.org/10.1056/NEJMoa0902905.

[41] Zhao TY, Wang BJ, Liu C, Liu J, Bu JQ, Liu Y, *et al*. Comparing 3-month and 1-year patency rates of no-touch great saphenous vein and pedicled left internal mammary artery in off-pump coro-

nary artery bypass grafting: a prospective non-inferiority study. Frontiers in Cardiovascular Medicine. 2025; 12: 1547482. https://doi.org/10.3389/fcvm.2025.1547482.

[42] Arslan G, Erol G, Kartal H, Demirdas E, Bolcal C. The Incidence of Atrial Fibrillation after On-Pump Versus Off-Pump Coronary Artery Bypass Grafting. The Heart Surgery Forum. 2021; 24: E645–E650. https://doi.org/10.1532/hsf.3873.

[43] Dieberg G, Smart NA, King N. On- vs. off-pump coronary artery bypass grafting: A systematic review and meta-analysis. International Journal of Cardiology. 2016; 223: 201–211. https://doi.org/10.1016/j.ijcard.2016.08.250.

[44] Wu N, Li J, Xu X, Yuan Z, Yang L, Chen Y, *et al*. Prediction Model of New Onset Atrial Fibrillation in Patients with Acute Coronary Syndrome. International Journal of Clinical Practice. 2023; 2023: 3473603. https://doi.org/10.1155/2023/3473603.

[45] Qin H, Si P, Hua K, Yang X. The value of off-pump coronary artery bypass grafting in the surgery for combined valvular and coronary heart disease. Frontiers in Medicine. 2024; 11: 1451778. https://doi.org/10.3389/fmed.2024.1451778.

[46] Moustafa A, Vyas R, Nazir S, Elzanaty AM, Eltahawy EA. D-32 | Non Touch Versus Conventional Vein Harvesting Techniques at 1-year After Coronary Artery Bypass Surgery: A Meta-analysis. Journal of the Society for Cardiovascular Angiography & Interventions. 2022; 100239. https://doi.org/10.1016/j.jscai.2022.100239.

[47] Deb S, Singh SK, de Souza D, Chu MWA, Whitlock R, Meyer SR, *et al*. SUPERIOR SVG: no touch saphenous harvesting to improve patency following coronary bypass grafting (a multi-Centre randomized control trial, NCT01047449). Journal of Cardiothoracic Surgery. 2019; 14: 85. https://doi.org/10.1186/s13019-019-0887-x.

[48] Kim YH, Oh HC, Choi JW, Hwang HY, Kim KB. No-Touch Saphenous Vein Harvesting May Improve Further the Patency of Saphenous Vein Composite Grafts: Early Outcomes and 1-Year Angiographic Results. The Annals of Thoracic Surgery. 2017; 103: 1489–1497. https://doi.org/10.1016/j.athoracsur.2016.09.024.

[49] Karan R, Kovačević-Kostić N, Kirćanski B, Čumić J, Terzić D, Milićević V, *et al*. Morphogenetic dispositions for variability in acute kidney injury after cardiac surgery: Pilot study. Frontiers in Medicine. 2022; 9: 943254. https://doi.org/10.3389/fmed.2022.943254.

[50] Xiao C, Yang M, Cao L, Chen F, Jing S, Tan Y, *et al*. The impact of intraoperative hypotension on postoperative acute kidney injury, mortality and length of stay following off-pump coronary artery bypass grafting surgery: a single-center retrospective cohort study. BMC Anesthesiology. 2024; 24: 224. https://doi.org/10.1186/s12871-024-02616-4.

[51] Ranucci M, Johnson I, Willcox T, Baker RA, Boer C, Baumann A, *et al*. Goal-directed perfusion to reduce acute kidney injury: A randomized trial. The Journal of Thoracic and Cardiovascular Surgery. 2018; 156: 1918–1927.e2. https://doi.org/10.1016/j.jtcvs.2018.04.045.

[52] Bradley CR, Bragg DD, Cox EF, El-Sharkawy AM, Buchanan CE, Chowdhury AH, *et al*. A randomized, controlled, double-blind crossover study on the effects of isoeffective and isovolumetric intravenous crystalloid and gelatin on blood volume, and renal and cardiac hemodynamics. Clinical Nutrition. 2020; 39: 2070–2079. https://doi.org/10.1016/j.clnu.2019.09.011.