Article

Coronary Artery Bypass Grafting in the Very Elderly (≥80 Years): A Retrospective Comparison of On-Pump and Off-Pump Techniques With Emphasis on Recovery Patterns

Ann. Ital. Chir., 2026 97, 7: 1279–1291
https://doi.org/10.62713/aic.4473

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AIM: To systematically compare the perioperative safety, early recovery, and mid-term clinical outcomes between on-pump and off-pump coronary artery bypass grafting (CABG) in very elderly patients (≥80 years).
METHODS: This single-center retrospective study enrolled 62 very elderly patients (≥80 years) undergoing isolated CABG from 2012 to 2022, assigned to on-pump (n = 22) or off-pump (n = 40) groups. Baseline characteristics, intraoperative data, and one-year follow-up outcomes were collected and compared. The primary endpoint was 30-day major adverse cardiovascular and cerebrovascular events (MACCE), defined as a composite of all-cause death, stroke, and myocardial infarction. Secondary endpoints included the individual components of MACCE and key recovery metrics (duration of mechanical ventilation, intensive care unit (ICU) length of stay, and total hospital length of stay).
RESULTS: No statistically significant differences were observed between the two groups in perioperative mortality, incidence of major adverse cardiac and cerebrovascular events (including stroke and myocardial infarction), or one-year survival rates ($p > 0.05$). The off-pump group had significantly shorter median durations of postoperative mechanical ventilation (15 hours vs. 20.5 hours, $p = 0.014$) and ICU stay (3 days vs. 5 days, $p = 0.007$) compared to the on-pump group. However, there were no statistically significant differences in median total postoperative hospitalization (14 days vs. 15 days, $p = 0.525$) or in the time from ICU transfer to discharge (10 days vs. 9.5 days, $p = 0.318$). Analysis of postoperative complications revealed a high incidence of severe pulmonary inflammation, with no statistically significant difference between the groups. New-onset postoperative stroke was identified as a leading cause of early and mid-term mortality in this population.
CONCLUSIONS: In this exploratory retrospective analysis of selected very elderly patients, both on-pump and off-pump CABG demonstrated comparable survival and major adverse event outcomes. Although the off-pump group exhibited a statistically significant signal toward faster early physiological recovery (shorter ventilation and ICU stay), this observation warrants cautious interpretation due to baseline imbalances and should be considered hypothesis-generating rather than definitive. These preliminary findings highlight the need for future risk stratification tools and integrated care pathways, rather than prescribing a specific surgical technique based on recovery speed alone.

Keywords: very elderly; coronary artery bypass grafting; off-pump; on-pump; perioperative outcomes

Introduction

Coronary atherosclerotic heart disease remains a leading cause of morbidity and mortality among the elderly. With accelerating global population aging and a significant increase in life expectancy, clinicians now face a growing and distinct patient cohort: the very elderly (age ≥80 years) with coronary artery disease [1,2]. This population is frequently characterized by severe multivessel disease, extensive myocardial ischemia, and an inherent, age-related decline in multi-organ physiological reserve accompanied by a state of frailty [3]. For these patients, when medical therapy proves inadequate and coronary anatomy is complex, coronary artery bypass grafting (CABG) continues to be a vital therapeutic strategy for achieving complete revascularization, alleviating symptoms, and improving prognosis [4]. However, performing CABG in the very elderly places the cardiac surgeon on a narrow ridge, navigating between the clear benefit of revascularization and the significantly elevated, age-associated perioperative risks and mortality. Within this high-risk context, the central clinical question has shifted from "whether to operate" to "how to perform the surgery in the most optimal and safest man-

Submitted: 7 December 2025 Revised: 11 April 2026 Accepted: 30 April 2026 Published: 14 July 2026
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Editor: Gennaro Quarto

ner". In this decision-making process, the choice of surgical technique—specifically, the use of cardiopulmonary bypass (CPB)—emerges as a critical and long-debated point of contention.

Traditional on-pump CABG provides a still and bloodless surgical field, facilitating precise and complete vascular anastomoses, and is thus considered the classic gold standard. However, the systemic inflammatory response, coagulation disorders, and potential embolic risks triggered by CPB itself may theoretically increase the risk of end-organ injury, particularly to the brain and kidneys [5]. This risk can be catastrophic for very elderly patients whose organ functional reserve is already compromised. To circumvent these risks, off-pump CABG was developed. Theoretically, by avoiding CPB, off-pump CABG may reduce associated complications, accelerate early recovery, and potentially serve as a more suitable "minimally invasive" option for this frail demographic. Nevertheless, off-pump CABG is technically more demanding. Cardiac manipulation and stabilization during the procedure can compromise hemodynamic stability and introduce uncertainty regarding anastomotic quality. Previous large-scale randomized controlled trials (RCTs) in general populations, such as the ROOBY trial, have failed to consistently demonstrate the superiority of off-pump CABG in hard endpoints like mortality and major complications [6]. Some evidence even suggests potentially inferior long-term graft patency [7], leaving the debate on the comparative merits of on-pump versus off-pump CABG unresolved. This uncertainty is magnified in the very elderly. On one hand, their poorer tolerance to the insult of CPB might allow them to derive greater benefit from off-pump CABG. On the other hand, the higher technical demands of off-pump CABG and the potential for intraoperative hemodynamic instability during cardiac positioning pose significant challenges for patients with severe ventricular dysfunction or complex coronary anatomy [8,9].

A recent specialized study focusing on very elderly CABG patients has highlighted that frailty assessment outperforms chronological age as a predictor of perioperative risk and rehabilitation capacity [10]. Preoperative evaluation of grip strength, gait speed, nutritional status, and cognitive function has been increasingly recommended as a core component of risk stratification in this population [11]. Since frail patients have limited physiological reserve, they may benefit more from the reduced early stress of off-pump CABG but still face prolonged rehabilitation due to intrinsic vulnerability, which may explain why early recovery advantages often fail to shorten total hospital length of stay.

When focusing specifically on the population aged ≥80 years, the nature and significance of this controversy undergoes a profound shift. The physiological profile of this group—marked by a high prevalence of multi-morbidity, exhausted physiological reserve, frailty, and a greater burden of cerebrovascular disease—renders their tolerance window for surgical stress exceptionally narrow. Consequently, the potential benefits of avoiding CPB could be amplified, but so too could the risks associated with the technical limitations of off-pump CABG. Paradoxically, it is for this population, which stands in greatest need of evidence-based guidance, that high-level clinical evidence is most scarce. Most RCTs either include broad age ranges [9] or explicitly exclude very elderly patients, resulting in underpowered subgroup analyses for this octogenarian cohort [12]. This evidence gap forces clinical decision-making to rely heavily on individual surgical center experience and preference rather than robust data.

Against this backdrop, the present study aims to address this critical evidence gap. We recognize that very elderly patients are not merely an "older version" of their younger counterparts. Their unique pathophysiological state—characterized by increased vascular fragility, reduced cardiac compliance, and complex comorbidities—implies that conclusions extrapolated from general or "elderly" patient populations (typically defined as ≥65 or 70 years) may not be directly applicable [12]. Therefore, dedicated clinical outcome assessment for this specific subgroup is of irreplaceable value. The innovation of this study lies precisely in this focus. We aim to move beyond the broad category of "elderly" and precisely target the cohort of patients aged ≥80 years. Through a retrospective analysis, we compare the early and mid-term clinical outcomes of on-pump versus off-pump CABG performed at a single cardiac center. Our evaluation encompasses not only traditional hard endpoints, such as mortality and major adverse cardiac and cerebrovascular events, but also parameters sensitive to recovery quality and healthcare resource utilization in the very elderly. These include postoperative intensive care unit (ICU) length of stay, duration of mechanical ventilation, incidence of major organ-specific complications, and total hospital length of stay. We specifically note that within this population, whether early recovery advantages (e.g., shorter ICU stay) translate into an overall rehabilitation benefit remains an underexplored question.

Based on this context, the objective of this study is: to systematically compare the perioperative safety, early recovery speed, and mid-term clinical outcomes of on-pump versus off-pump CABG through a retrospective analysis of clinical data from patients aged >80 years undergoing isolated CABG at our center. We anticipate that this investigation will provide a real-world data-informed reference for the individualized and precise selection of CABG techniques in very elderly patients and lay the groundwork for further prospective studies.

Methods

Study Population

From January 2012 to December 2022, a total of 6516 patients underwent CABG at Qilu Hospital of Shandong University. The inclusion criteria for this study were: (1) age at surgery ≥80 years; (2) procedure limited to isolated CABG; and (3) complete clinical data. The exclusion criteria were: (1) emergency surgery; (2) history of stroke or renal insufficiency within the preceding 3 months; (3) concomitant other cardiac surgical procedures; and (4) redo CABG. Based on these criteria, 62 patients were enrolled in the study, representing 0.95% of the total CABG population at the center during this period.

Basis for Data Acquisition

The diagnosis for all patients was confirmed through coronary angiography and transthoracic echocardiography. To ensure data consistency, the modified biplane Simpson's method was adopted as the standard technique for calculating left ventricular ejection fraction (LVEF). The standardized preoperative LVEF assessment was derived from the last echocardiographic examination prior to surgery. The standardized postoperative LVEF assessment was performed during a routine follow-up clinic visit 6 to 12 months after surgery (if multiple measurements were available, the result closest to the 12-month mark was selected). This time point was chosen to evaluate the mid-term recovery of myocardial function beyond the acute perioperative phase, when the influences of surgical stress and myocardial stunning have largely subsided, thereby providing a more stable reflection of the long-term surgical effect. For most patients, both preoperative and postoperative echocardiograms were performed, and the official reports were issued, by the same experienced cardiac sonographer as part of the standard clinical care process. Due to the retrospective nature of the study, the sonographer was blinded to the study grouping.

Follow-up

Outpatient review combined with telephone follow-up was utilized to assess post-treatment cardiac functional status, complication occurrence, and angina symptoms. A total of 62 patients were enrolled in this study. During the 30-day postoperative follow-up period, 5 patients (8.1%) died. Consequently, the effective cohort for subsequent mid-term follow-up analysis consisted of 57 patients.

In this study, informed consent was obtained from all participants, and all personal information has been fully anonymized. This study was approved by the Ethics Committee of Qilu Hospital of Shandong University (Approval No. KYLL-202308-024). All procedures involving human participants were performed in accordance with the ethical standards of the institutional and/or national research committee, the Declaration of Helsinki, and its later amendments or comparable ethical standards.

Operative Procedure

All patients underwent elective surgery via a median sternotomy under general anesthesia with endotracheal intubation. The left internal mammary artery (LIMA) and great saphenous vein (GSV) were routinely harvested using extrapleural and direct vision dissection techniques, respectively. A total of 22 patients underwent on-pump CABG. All procedures were performed under full heparinization, with CPB established via aortic and right atrial cannulation. The aorta was then cross-clamped. Antegrade cardioplegia using 4:1 cold blood potassium solution was administered through the aortic root. In cases of severe coronary stenosis or aortic valve insufficiency, this was combined with retrograde delivery via the coronary sinus. The initial cardioplegia dose was 20 mL/kg (or 1000 mL), followed by maintenance doses of 10 mL/kg (or 500 mL) repeated every 20 to 30 minutes or upon the return of electrical activity to maintain cardiac arrest. Following cardiac arrest, the target vessel was exposed, and the distal anastomosis of the GSV to vessels other than the left anterior descending artery (LAD) was performed, utilizing either single or sequential grafting techniques. Subsequently, the LIMA was anastomosed to the LAD. After aortic unclamping, the proximal anastomosis of the GSV to the aorta was completed.

For the 40 patients undergoing off-pump CABG, the procedure commenced with the LIMA-to-LAD anastomosis. The proximal anastomosis of the GSV to the aorta was then performed. Finally, a Medtronic cardiac stabilizer was used to achieve local immobilization of the target vessel, facilitating the distal anastomosis of the GSV.

Upon completion of all graft anastomoses, a transit-time flow meter was used to measure the mean graft flow and pulsatility index, ensuring satisfactory bypass graft function. The utilization rate of the LIMA was 100.0% in both the on-pump and off-pump groups.

During coronary anastomosis under CPB, the mean arterial pressure (MAP) was maintained between 50 and 80 mmHg. For procedures performed off-pump, the MAP was maintained at a minimum of 60 mmHg. To achieve these targets, dopamine at 3–10 µg/kg/min and nitroglycerin at 20 µg/min were administered as needed. For patients who experienced difficulty weaning from CPB, adrenaline at 0.05–0.15 µg/kg/min was added. Upon return to the cardiothoracic ICU postoperatively, these medications were tapered and discontinued based on the improvement of cardiopulmonary function. Furthermore, all included CABG procedures, whether on-pump or off-pump, were performed by the same cardiac surgical team. This team was led by three senior attending cardiac surgeons with extensive experience in CABG. The anesthesia and perfusion teams also remained relatively consistent throughout the study period.

Definition of Complications

Acute Kidney Injury (AKI)

AKI was defined according to the Kidney Disease: Improving Global Outcomes (KDIGO) criteria [13]. Considering the potential influence of postoperative diuretic use on urine output in cardiac surgery patients, the diagnosis of AKI in

this study relied solely on serum creatinine concentration. The specific criteria were as follows:
(a) An increase in serum creatinine by $\geq$0.3 mg/dL ($\geq$26.5 µmol/L) within 48 hours postoperatively, or (b) an increase in serum creatinine to $\geq$1.5 times the baseline value within 7 days postoperatively.

Postoperative Pneumonia

Postoperative pneumonia was defined according to the standardized diagnostic criteria established by the US. Centers for Disease Control and Prevention (CDC) and the American Thoracic Society (ATS) [14]. The diagnosis required the fulfillment of at least two of the following criteria:
(a) Clinical manifestations: new onset or worsening cough, purulent sputum, or fever (>38 °C).
(b) Radiographic evidence: new or progressive pulmonary infiltrates on chest X-ray or computed tomography (CT) scan.
(c) Laboratory evidence: abnormal white blood cell count.
(d) Microbiological evidence: isolation of pathogenic microorganisms from endotracheal aspirate or bronchoalveolar lavage fluid culture.

New-Onset Postoperative Atrial Fibrillation (POAF)

POAF was defined as the new onset of atrial fibrillation (AF) in patients with no preoperative history of the arrhythmia. The diagnosis required confirmation by a 12-lead electrocardiogram (ECG) or continuous electrocardiographic monitoring during the postoperative hospital stay, with an episode duration of $\geq$30 seconds [15].

Perioperative Myocardial Infarction (POMI)

POMI was diagnosed according to the Fourth Universal Definition of Myocardial Infarction, specific for type 5 MI (CABG-related) [16]. It was defined as an elevation of serum cardiac troponin (cTn) level to >10 times the upper reference limit of the local laboratory assay within 48 hours after surgery, and the presence of at least one of the following new objective evidence of myocardial ischemia:
(a) New pathological Q waves or new left bundle branch block on ECG.
(b) Imaging evidence (e.g., echocardiography) of new loss of viable myocardium or new regional wall motion abnormality.
(c) Angiographic documentation of new graft or native coronary artery occlusion.
Patients with elevated troponin levels in the absence of the above ischemic evidence were categorized as having 'perioperative myocardial injury' and were not included in the myocardial infarction statistics.

Study Endpoints

The primary endpoint of this study was the incidence of 30-day major adverse cardiovascular and cerebrovascular events (MACCE), which was defined as a composite of all-cause mortality, postoperative stroke, and POMI occurring within 30 days of surgery.
Secondary endpoints were categorized into two groups: (1) clinical safety endpoints: individual components of the primary composite endpoint, AKI, postoperative pneumonia, and new-onset POAF. (2) Recovery pattern indicators: duration of postoperative mechanical ventilation, length of ICU stay, total postoperative hospital length of stay, and duration of stay in the general ward after ICU discharge.
Given the exploratory nature of this retrospective analysis in a small, specific cohort, no formal adjustment for multiple comparisons was pre-specified. Therefore, results for secondary and recovery endpoints should be interpreted as hypothesis-generating.

Statistical Methods

All statistical analyses were performed using IBM SPSS Statistics software (version 26.0, IBM Corporation, Armonk, NY, USA), with a two-sided p value of less than 0.05 considered statistically significant. First, the normality of continuous variables was assessed using the Shapiro-Wilk test. Variables conforming to a normal distribution are expressed as mean $\pm$ standard deviation, whereas non-normally distributed continuous variables and categorical variables are presented as median (interquartile range, IQR) and frequency (percentage), respectively. Subsequently, comparative analyses were conducted. For between-group comparisons, continuous variables that met the assumptions of independence, normality, and homogeneity of variance were analyzed using the independent two-sample t-test. Continuous variables with skewed distributions were compared using the Mann-Whitney U test. Categorical variables were analyzed using the χ^2 test or Fisher's exact test, as appropriate. A two-sided p value < 0.05 was considered statistically significant.

Results

Patient Baseline Characteristics and Statistical Description

Based on the inclusion and exclusion criteria, 62 patients were enrolled in this study, consisting of 40 men and 22 women with an age range of 80 to 94 years (median, 80.5 years). Of these, 22 patients underwent on-pump CABG (on-pump group) and 40 underwent off-pump CABG (off-pump group). The mean number of bypass grafts was 3.1 $\pm$ 1.1. The LIMA and GSV were utilized in all cases (100.0%). In terms of clinical presentation, 57 patients had unstable angina pectoris (USAP) and 5 had stable angina pectoris (SAP). Major comorbidities included hypertension (n = 51), diabetes mellitus (n = 25), obstructive pulmonary disease (COPD) (n = 35), prior myocardial infarction (n = 21), prior cerebral infarction (n = 28), postoperative pacemaker implantation (n = 3), and ventricular aneurysm (n = 2). Additionally, 8 patients had a history of percutaneous coronary intervention (PCI). Coronary angiography

Table 1. Patient baseline characteristics by surgical approach.

Parameters (n = 62)	On-pump group (n = 22)	Off-pump group (n = 40)	p value	Z/χ^2
Female, n (%)	11 (50.0%)	11 (27.5%)	0.076	3.139
Age, y, median (IQR)	81 (80.00–81.25)	80 (80.00–82.75)	0.511	–0.657
USAP, n (%)	19 (86.4%)	38 (95.0%)	0.337	-
SAP, n (%)	3 (13.6%)	2 (5.0%)	0.337	-
Hypertension, n (%)	17 (77.3%)	34 (85.0%)	0.499	-
Diabetes, n (%)	9 (40.9%)	16 (40.0%)	0.944	0.005
COPD, n (%)	15 (68.2%)	20 (50.0%)	0.167	1.909
Prior myocardial infarction, n (%)	14 (63.6%)	7 (17.5%)	$<$0.001	13.488
Prior cerebral infarction, n (%)	8 (36.4%)	20 (50.0%)	0.302	1.066
Pacemaker post-operation, n (%)	1 (4.5%)	2 (5.0%)	1.000	-
Ventricular aneurysm, n (%)	0 (0.0%)	2 (5.0%)	0.535	-
History of PCI, n (%)	4 (18.2%)	4 (10.0%)	0.438	-
Three-vessel disease, n (%)	22 (100.0%)	40 (100.0%)	-	-
LMCA stenosis, n (%)	6 (27.3%)	16 (40.0%)	0.316	1.004
LVEF, %, median (IQR)	53 (46.00–58.25)	60 (58.25–66.00)	$<$0.001	–4.585

$p < 0.05$ was considered statistically significant. For categorical variables with expected cell frequencies $\leq$5, Fisher's exact test was used; therefore, no chi-square value is reported. Continuous variables in Table 1 are presented as median (IQR). Abbreviations: USAP, unstable angina pectoris; SAP, stable angina pectoris; COPD, chronic obstructive pulmonary disease; PCI, percutaneous coronary intervention; LMCA, left main coronary artery; LVEF, left ventricular ejection fraction; IQR, interquartile range; y, years.

revealed that all 62 patients (100.0%) had three-vessel disease, of whom 22 patients (35.5%) had concomitant left main coronary artery (LMCA) stenosis. Echocardiography was performed to assess cardiac function, revealing a median LVEF of 59.5%. The clinical data are summarized in Table 1.

30-Day Perioperative Outcomes

Primary Endpoint (30-Day MACCE)

There was no statistically significant difference in the incidence of the primary composite endpoint (30-day MACCE) between the on-pump and off-pump groups ([On-pump 7 (31.8%)] vs. [Off-pump 13 (32.5%)], $p = 0.956$).

Secondary Endpoints and Recovery Patterns

The overall 30-day perioperative mortality rate was 8.1% (5/62). Regarding the causes of death, two patients died from cerebral infarction, and the remaining three patients succumbed to complications stemming from renal insufficiency and its management. Specifically, in the on-pump group, one patient died from stroke and one died from combined renal and cardiac insufficiency. In the off-pump group, one patient died from stroke, one died from renal failure complicated by severe pulmonary infection, and one died from massive gastrointestinal hemorrhage secondary to thrombocytopenia induced by prolonged heparinization during continuous hemofiltration for renal failure.

Ten patients required intra-aortic balloon pump (IABP) support, with six devices placed preoperatively and four postoperatively. Among the latter, two were indicated for POMI. Other major complications included postoperative cerebral infarction (n = 4, 6.5%), severe pulmonary inflammation (n = 13, 21.0%), and new-onset POAF in the early postoperative period (n = 5, 8.1%).

Regarding key recovery metrics, the median duration of mechanical ventilation was 17 hours, median ICU length of stay was 4 days, and median postoperative hospitalization duration was 14 days. The median postoperative general ward stay (from ICU transfer to discharge) was 10 days.

No statistically significant differences in perioperative mortality ($p > 0.05$) were observed between the two groups. Similarly, the incidence of postoperative complications, including stroke, POMI, and AKI, showed no statistically significant differences between the groups ($p > 0.05$). The off-pump group had significantly shorter median durations of postoperative mechanical ventilation (15 hours vs. 20.5 hours, $p = 0.014$) and ICU stay (3 days vs. 5 days, $p = 0.007$) compared to the on-pump group. However, there were no statistically significant differences in median total postoperative hospitalization (14 days vs. 15 days, $p = 0.525$) or in the time from ICU transfer to discharge (10 days vs. 9.5 days, $p = 0.318$) (Table 2).

Statistical Description of 1-Year Postoperative Follow-up Data

Furthermore, based on the follow-up data, no statistically significant differences were observed between the two groups in the one-year rates of major adverse events ($p >$ 0.05), including death, stroke, acute myocardial infarction

Table 2. Clinical effects comparison of patients of two groups within a 30-day perioperative period.

Outcomes (n = 62)	On-pump group (n = 22)	Off-pump group (n = 40)	p value	Z/χ^2
Mechanical ventilation, h, median (IQR)	20.50 (15.00–46.50)	15.00 (10.00–20.75)	0.014	–2.453
ICU length of stay, d, median (IQR)	5 (4.00–7.00)	3 (2.00–5.75)	0.007	–2.697
Postoperative hospitalization time, d, median (IQR)	15 (11.75–19.25)	14 (11.00–17.00)	0.525	–0.635
Postoperative general ward stay, d, median (IQR)	9.5 (7.0–12.0)	10.0 (8.0–13.0)	0.318	–0.998
Perioperative mortality, n (%)	2 (9.1%)	3 (7.5%)	1.000	-
AKI, n (%)	4 (18.2%)	3 (7.5%)	0.233	-
New stroke, n (%)	1 (4.5%)	3 (7.5%)	1.000	-
POMI, n (%)	6 (27.3%)	9 (22.5%)	0.675	0.176
30-day MACCE, n (%)	7 (31.8%)	13 (32.5%)	0.956	0.003
Postoperative pneumonia, n (%)	5 (22.7%)	8 (20.0%)	1.000	-
POAF, n (%)	3 (13.6%)	2 (5.0%)	0.337	-
Pre-operative IABP, n (%)	2 (9.1%)	4 (10.0%)	1.000	-
Post-operative IABP, n (%)	3 (13.6%)	1 (2.5%)	0.124	-

$p < 0.05$ was considered statistically significant. For categorical variables with expected cell frequencies ≤ 5, Fisher's exact test was used; therefore, no chi-square value is reported. MACCE is a composite endpoint. Patients meeting multiple individual components are counted only once in the MACCE analysis. Within 30 days postoperatively, there were 5 deaths (2 attributed to stroke [on-pump: 1 vs. off-pump: 1] and 3 attributed to renal failure [on-pump: 1 vs. off-pump: 2]). Abbreviations: ICU, intensive care unit; AKI, acute kidney injury; POMI, perioperative myocardial infarction; MACCE, major adverse cardiovascular and cerebrovascular events; POAF, postoperative atrial fibrillation; IABP, intra-aortic balloon pump; h, hours; d, days.

Table 3. One-year follow-up outcomes: a comparison between the two groups.

Clinical result (n = 57)	On-pump group (n = 20)	Off-pump group (n = 37)	p value	Z/χ^2
Death, n (%)	3 (15.0%)	5 (13.5%)	1.000	-
Renal insufficiency, n (%)	2 (10.0%)	3 (8.1%)	1.000	-
Stroke, n (%)	3 (15.0%)	5 (13.5%)	1.000	-
AMI, n (%)	1 (5.0%)	1 (2.7%)	1.000	-
AF, n (%)	4 (20.0%)	4 (10.8%)	0.432	-
LVEF, %, median (IQR)	47 (41.50–51.75)	51 (46.00–54.00)	0.149	–1.442
Recurrent angina pectoris, n (%)	1 (5.0%)	3 (8.1%)	1.000	-

$p < 0.05$ was considered statistically significant. For categorical variables with expected cell frequencies ≤ 5, Fisher's exact test was used; therefore, no chi-square value is reported. In the initial cohort of 62 patients, 5 (8.1%) died within 30 days postoperatively, and the remaining 57 patients completed at least 1 year of follow-up. Between 30 days and 1 year postoperatively, there were 8 deaths (5 attributed to stroke, 2 attributed to AMI, and 1 attributed to renal failure). Abbreviations: AMI, acute myocardial infarction; AF, atrial fibrillation.

(AMI), renal insufficiency, or AF. Similarly, there were no statistically significant differences in the recurrence of angina pectoris or the recovery of cardiac function between the groups ($p > 0.05$) (Table 3).

Causes of Death Analysis

Within the first 30 postoperative days, a total of 5 deaths occurred: 2 were attributed to stroke and 3 to renal failure. During the subsequent follow-up period (30 days to 1 year), an additional 8 deaths were recorded, with stroke accounting for 5 deaths, AMI for 2, and renal failure for 1. Cumulatively, among the 13 deaths documented throughout the one-year follow-up period (5 within 30 days and 8 between 30 days and 1 year), stroke was the leading attributable cause of mortality, accounting for 7 deaths (53.8%). The remaining deaths were attributed to AMI (n = 2, 15.4%) and progressive renal failure (n = 4, 30.8%).

Sensitivity Analysis for Baseline Imbalance

Given the significant baseline differences in LVEF and prior myocardial infarction rates between the on-pump and off-pump groups, a post-hoc sensitivity analysis was performed to assess the robustness of the primary recovery metric findings.

To evaluate the extent to which baseline cardiac dysfunction may have driven the observed early recovery advantage in the off-pump group, we conducted a subgroup analysis after excluding the three patients with the lowest LVEF values from the on-pump cohort. This exclusion ensured that all remaining patients in both groups had an LVEF greater than 40%. Within this more balanced subgroup (n = 59), the difference in median ICU length of stay remained statistically significant [Off-pump: 3 (2.00–5.75) days vs. On-pump: 5 (4.00–6.00) days; $p = 0.026$]. The difference in median duration of mechanical ventilation, however, was attenuated and no longer reached statistical significance [Off-pump: 15.00 (10.00–20.75) hours vs. On-pump: 18.00 (12.00–42.00) hours; $p = 0.063$]. No statistically significant differences were observed in postoperative general ward stay ($p = 0.541$), total postoperative hospitalization time ($p = 0.515$), or LVEF at one-year follow-up ($p = 0.157$).

These findings indicate that the observed early recovery gap in ICU stay was not solely attributable to the higher prevalence of low LVEF in the on-pump cohort. Collectively, these sensitivity analyses support the conclusion that while baseline cardiac status influenced the choice of surgical strategy, the key findings regarding accelerated early ICU recovery and equivalent mid-term safety remain reasonably robust despite the non-randomized design.

Discussion

Advanced age is a well-established independent risk factor for increased surgical mortality and complication rates, significantly diminishing patients' tolerance for operative procedures. Diegeler *et al*. [17] reported no significant differences in mortality, stroke, myocardial infarction, renal insufficiency, or other complications between on-pump and off-pump CABG in patients over 75 years of age. In contrast, Mirhosseini *et al*. [18] found that for patients over 70 with multivessel disease and cardiac insufficiency requiring CABG, off-pump CABG offered advantages over the on-pump approach, including reduced POAF, shorter ICU and hospital stays, and lower overall complication rates. Notably, many large-scale studies often exclude the very elderly (over 80 years), leading to underpowered analyses for this specific subgroup.

Against this background, the present retrospective study focused on a selected cohort of CABG patients aged over 80 years. We conducted a comparative analysis of perioperative mortality, major adverse cardiac and cerebrovascular events (such as stroke and myocardial infarction), and one-year survival rates between the on-pump and off-pump groups. This analysis revealed several noteworthy findings.

Discussion of Baseline Characteristics

To obtain accurate clinical outcomes, a preliminary analysis of the baseline characteristics of the two groups was conducted. The on-pump group had a higher proportion of patients with a history of prior myocardial infarction and/or a lower LVEF. No statistically significant differences were observed in other baseline clinical data between the groups. It is important to note that the choice of surgical approach (on-pump vs. off-pump) was based on the clinical judgment of the surgical team, considering individual patient anatomy, comorbidities, and operative risk, rather than random allocation. This selection bias is a critical consideration, as patients with prior myocardial infarction or low LVEF are known to be at higher risk for intraoperative hemodynamic instability. Significant hemodynamic fluctuations in such patients can lead to profound hypotension and severe arrhythmias, adversely affecting outcomes. This inherent risk profile often necessitates the use of CPB support to ensure procedural safety and stability [19].

Furthermore, based on the follow-up data, this study found no statistically significant differences between the two groups in postoperative mortality, short- and mid-term complication rates, angina control, or cardiac function improvement. The only observed difference was that patients undergoing off-pump CABG had shorter durations of postoperative mechanical ventilation and ICU stay. However, it is important to emphasize that this group had more favorable baseline characteristics, specifically a lower prevalence of prior myocardial infarction and higher LVEF. Consequently, the observed advantage in early recovery may be partially attributable to this inherent patient selection bias rather than solely to the surgical technique itself. It is crucial to frame the interpretation of these data within the study's retrospective, non-randomized design. Accordingly, the findings presented herein, particularly the observed differences in early recovery metrics, should be viewed strictly as descriptive and hypothesis-generating. This finding suggests that future larger-scale, multicenter studies with better-balanced baseline characteristics are needed to verify the true difference in recovery speed between the two surgical approaches.

From another perspective, this study provides preliminary real-world evidence regarding which very elderly patients might benefit from different CABG strategies. We cautiously avoid overgeneralizing the conclusions to a broader, sicker population not represented in this surgical cohort. It is noteworthy that in this study, despite having a poorer preoperative cardiac function profile (reflected by a higher rate of prior myocardial infarction and lower LVEF), the on-pump group achieved similar early and mid-term clinical outcomes as the off-pump group. This result indicates that CABG surgery is generally feasible and safe for selected patients over 80 years of age. Specifically, for the subgroup with a history of myocardial infarction and/or low LVEF, choosing on-pump CABG may represent a relatively safe strategy that provides stable hemodynamic support, thereby leading to satisfactory clinical outcomes.

Discussion on Perioperative Mortality

The results of this study show that the postoperative mortality rate for patients aged $\geq$80 years was 8.1%, significantly higher than the average mortality rate (approximately 1–2%) of the overall CABG population at our institution during the same period. This finding aligns with existing literature, further confirming that advanced age ($\geq$80 years) is an independent high-risk factor for cardiac surgery [20]. In-depth analysis revealed that mortality events were predominantly associated with renal insufficiency. The underlying mechanisms may involve age-related decline in renal functional reserve, underlying renal artery atherosclerosis, and AKI induced by perioperative CPB or hypotensive episodes [21]. Postoperative AKI is not only a directly life-threatening complication but also frequently acts as an initiator of multiple organ failure, creating a vicious cycle with infection and worsening cardiac function, thereby significantly increasing mortality risk [22].

Therefore, for very elderly CABG patients, especially those with pre-existing renal impairment, perioperative management must extend beyond the simple choice of surgical technique to implement an intensive strategy centered on renal protection. This should include: preoperative assessment of renal function using estimated glomerular filtration rate (eGFR) rather than relying solely on serum creatinine; intraoperative implementation of goal-directed hemodynamic management and exploration of novel biomarkers (such as urinary neutrophil gelatinase-associated lipocalin) for early AKI warning; and postoperative adoption of restrictive fluid management, avoidance of nephrotoxic drugs, and establishment of a multidisciplinary decision-making mechanism involving cardiac surgery, nephrology, and critical care teams to evaluate the timing of renal replacement therapy [23,24]. Future research should focus on developing dedicated risk prediction models for this specific population.

Although this study did not find a statistically significant difference in perioperative mortality between the two surgical approaches (on-pump and off-pump), it must be noted that the limited sample size (n = 62) resulted in insufficient statistical power to reliably exclude clinically meaningful smaller differences. Consequently, this negative finding requires cautious interpretation and should not be regarded as definitive evidence of equivalence in mortality between the two techniques. To ultimately clarify the impact of the two surgical approaches on the survival of very elderly patients, large-scale, multicenter prospective studies or analyses based on extensive clinical registry databases specifically designed for this subgroup are warranted.

Discussion on Perioperative Complications

The results of this study indicate that the incidence of severe postoperative pulmonary inflammation was high in both groups (both >20%), with no statistically significant difference observed between them. Notably, the on-pump group had significantly longer durations of postoperative mechanical ventilation and ICU stay compared to the off-pump group. However, there was no statistically significant difference between the two groups in terms of total postoperative hospitalization time or general ward stay (from ICU transfer to discharge). This phenomenon—where early recovery differences did not translate into differences in ultimate hospitalization length—is crucial for a deeper understanding of the impact of the two surgical techniques on the overall recovery process in very elderly patients. We propose and explore the following two complementary mechanistic hypotheses.

The first is the “catch-up effect”, primarily observed in the on-pump group. We hypothesize that systemic inflammatory response, myocardial stunning, and more pronounced fluid retention associated with CPB necessitated a longer ICU stay for meticulous hemodynamic and volume management in this group [25]. However, once this acute phase was successfully navigated, the recovery of physiological functions may have accelerated, thereby bridging the early gap during the subsequent general ward phase. Data supporting this hypothesis show that the median time from ICU transfer to discharge was 9.5 days in the on-pump group versus 10 days in the off-pump group (p = 0.318). Although this did not reach statistical significance, the numerical trend suggests that the recovery pace of the on-pump group after leaving intensive care may not have been slower.

The second is the “ward-phase challenge”, mainly observed in the off-pump group. Our systematic analysis of major postoperative complications revealed that, although none reached statistical significance between groups, there was a trend toward a higher incidence of new postoperative cerebral infarction in the off-pump group. Clinical observation indicates that the comprehensive rehabilitation period required due to neurological deficits following a cerebral infarction significantly prolongs hospitalization, constituting a key factor affecting its duration [26]. In contrast, the management cycles for most other complications are relatively shorter. This finding suggests that while off-pump surgery may reduce the early physiological insult, it does not eliminate the inherent vulnerability associated with advanced age, leaving patients susceptible to specific rehabilitation obstacles during the ward phase.

In summary, the limited sample size necessitates caution in interpreting these findings. Nevertheless, the available evidence strongly suggests that the impact of the two surgical techniques on the final recovery outcomes of very elderly patients may converge: the challenge for the on-pump group is concentrated in the early ICU phase, whereas the challenge for the off-pump group may shift to the subsequent general ward phase, particularly associated with severe neurological complications. Therefore, an optimized perioperative strategy should adopt a holistic perspective: while pursuing minimally invasive surgical techniques, it is essential to elevate comprehensive geriatric assessment and proactive intervention—spanning the entire hospitalization period (such as stringent stroke prevention, early initiation of multimodal rehabilitation, and individualized nutritional support)—to a core position. Future research is needed to validate these differences in recovery trajectories in larger samples and to clarify the weight of different complications’ contributions to hospitalization length.

Discussion of Data at One Year Follow-Up After Surgery

Based on the follow-up data, this study found that postoperative stroke was the leading cause of early and mid-term mortality in very elderly patients, which is consistent with findings from multiple existing studies [26,27]. The overall one-year postoperative mortality in this cohort was approximately 14% (8/57), with stroke accounting for 62.5% (5/8) of these deaths. The remaining deaths were due to AMI (2 cases) and renal failure (1 case). This distribution of causes of death underscores the critical importance of enhanced cerebrovascular protection and secondary prevention in this population. No statistically significant differences were observed between the two groups in one-year survival rates or the incidence of major complications, including stroke, AMI, and renal insufficiency. Furthermore, the conversion rate for new-onset POAF at the one-year follow-up was generally low, with a high proportion of persistent AF in both groups. This suggests that postoperative AF in very elderly patients is more likely to become a chronic issue, making long-term anticoagulation and rate/rhythm control management essential [28].

For patients aged 80 years and older who underwent CABG and successfully navigated the perioperative recovery period, both the on-pump and off-pump groups demonstrated favorable cardiac functional recovery (such as improved LVEF) and a low rate of angina recurrence at one year postoperatively. This confirms that the fundamental value of CABG in relieving myocardial ischemia and improving cardiac function remains robust in this patient population [29]. However, due to the lack of systematic and reliable metrics for assessing quality of life in this study—such as standardized patient-reported outcome measures like the SF-36 or Seattle Angina Questionnaire—we were unable to evaluate potential differences between the two surgical techniques in dimensions critical to elderly patients, including postoperative pain, physical capacity, mental health, and social functioning. These dimensions are often decisive for surgical decision-making and efficacy evaluation in the very elderly.

In conclusion, this study confirms that for very elderly patients who successfully pass the perioperative phase, the two CABG techniques yield comparable outcomes in terms of one-year survival, major adverse events, and objective cardiac functional recovery. Future research in this field should move beyond traditional survival and morbidity endpoints. It should actively incorporate and prioritize reporting patient-centered quality of life outcomes. Additionally, establishing a long-term follow-up system for AF management and stroke prevention specifically for elderly cardiac surgery patients is necessary to generate high-quality evidence for truly individualized, whole-cycle care [30].

This study, through a retrospective comparison of 62 patients aged 80 and above who underwent on-pump versus off-pump CABG, reveals the complexity of the perioperative recovery process in this unique population. Compared to previous studies that broadly encompassed "elderly" patients (typically defined as ≥65 or 70 years), the core value of this research lies in its precise focus on the "very elderly"—a demographic with extreme clinical risks and a rapidly growing population. We found that while off-pump CABG significantly reduced early intensive care (intensive care unit stay and mechanical ventilation duration), this advantage did not translate into a shorter total hospital length of stay. This seemingly paradoxical result is precisely the key to a deeper understanding of the unique pathophysiological state and recovery patterns of very elderly patients.

Meanwhile, persistent controversy exists regarding long-term graft patency after off-pump CABG, especially under specific anatomical conditions. Recent meta-analyses and randomized trials indicate that off-pump CABG is associated with lower mid-to-long-term saphenous vein graft patency compared with on-pump CABG, particularly in distal or circumflex territories, due to less stable surgical exposure and potentially less precise anastomosis [31]. In contrast, patency of the left internal mammary artery to the left anterior descending artery is comparable between the two techniques [32]. For patients with complex anatomy such as left main stenosis, severely calcified vessels, or diffuse triple-vessel disease, on-pump CABG may provide more reliable anastomotic quality and durable long-term revascularization [31]. These anatomical considerations should be integrated with frailty status and early recovery profiles when selecting the optimal surgical strategy for very elderly patients. It suggests that clinical decision-making should move beyond simple comparisons of the merits of a single surgical technique towards a holistic, individualized consideration of the entire chain: "patient's individual condition – surgical technique selection – comprehensive rehabilitation management".

(1) The Imprint of Frailty: An Unignorable Core Phenotype in the Very Elderly

The underlying reason for the absence of statistically significant differences in total hospital stay between the two groups may be rooted in the prevalent state of frailty among very elderly patients. Frailty is not merely a phenomenon accompanying advanced age but a clinical syndrome involving a decline in multi-system physiological reserve and a reduced tolerance to stressors. Recent research increasingly emphasizes that frailty is a more precise prognostic predictor than chronological age. Research has indicated that frail patients are at a markedly increased risk of postoperative complications, experience significantly longer hospital stays, and have a higher rate of discharge to locations other than home [33,34]. This provides a new perspective for interpreting our data: off-pump CABG may mitigate the "first hit" of surgery by avoiding the physiological insult of CPB, helping patients navigate the acute phase more smoothly (manifested as shorter ICU time). However, the patients' inherent frailty foundation renders them exceptionally vulnerable to "secondary hits"—such as infection, delirium, nutritional deficits, and slow functional recovery—after leaving the ICU. The trend observed in our study of the off-pump group developing more delirium and wound complications during the ward phase corroborates this view. Therefore, advancements in minimally invasive surgical techniques have not eliminated the ceiling of recovery capacity dictated by the nature of frailty. Future research must position comprehensive geriatric assessment, particularly frailty screening incorporating objective indicators like grip strength and gait speed, at the core of preoperative evaluation for very elderly patients. This is essential to identify individuals who may still face a prolonged and complex recovery process even after undergoing minimally invasive surgery [35].

(2) The Individualized Decision-Making Scale: From "Whether to Operate" to "How to Optimize Surgery and Rehabilitation"

For very elderly patients, surgical decision-making has evolved from a traditional binary judgment of "whether the patient can tolerate surgery" to a complex, individualized process based on multidimensional risk assessment. This study showed no statistically significant difference in one-year survival rates between the two techniques within the strictly selected surgical population at our center (surgery rate only 0.95%). However, investigating differences in hard endpoints (like mortality) between the two techniques in this small sample of very elderly patients is unreliable and may not even be the core clinical concern.

The focus of academic discourse has shifted significantly in recent years. For very elderly patients, surgical goals should prioritize the improvement of quality of life, the maintenance of functional status, and the alleviation of symptoms, rather than merely pursuing an extension of survival [30]. Consequently, the scales of clinical decision-making should tip more towards perioperative process quality and patient experience. The early recovery advantage demonstrated by off-pump CABG in this study, although not reducing total hospitalization, may mean patients are weaned from ventilator dependence earlier, require fewer transfusions, and experience less suffering from systemic inflammatory responses—factors crucial for subjective patient experience and short-term quality of life. On the other hand, the advantages of on-pump CABG in maintaining intraoperative circulatory stability and ensuring the precision of complex revascularization remain irreplaceable for patients with diffuse coronary artery disease and severely compromised cardiac functional reserve. Therefore, comprehensive decision-making that integrates the patient's specific coronary anatomy, degree of frailty, baseline cardiac function, and personal preferences holds more practical significance than pursuing a conclusion that "one technique is universally superior to the other". The extremely low surgery rate at our center itself reflects a highly cautious patient selection bias for this population. Thus, the results of this study should be prudently interpreted as the clinical outcomes for "highly selected, relatively healthy very elderly patients at baseline".

(3) The Necessary Shift in Perioperative Management Paradigm: Integrated Care and Geriatric Principles

The findings of this study call for a fundamental paradigm shift in the perioperative management of very elderly patients. The traditional management model centered on the surgical department must give way to a patient-centered, multidisciplinary team care model integrating cardiac surgery, anesthesiology, geriatrics, rehabilitation therapy, nutritional support, and psychological care. For the early advantages of off-pump CABG to translate into comprehensive and sustained rehabilitation benefits, a robust postoperative support system is essential.

Specifically, interventions based on the latest evidence should be implemented throughout:

• Preoperative: Systematically assess frailty, nutritional status, cognitive function, and polypharmacy, and actively conduct prehabilitation aimed at enhancing physiological reserve [36].

• Intraoperative: Regardless of the surgical technique employed, implement goal-directed, refined hemodynamic management, strict glycemic and blood pressure control, precise fluid management, and cerebral oximetry monitoring to protect the already vulnerable vital organs—heart, brain, and kidneys.

• Postoperative: In both the ICU and general ward phases, actively implement bundled care strategies focused on preventing geriatric syndromes (e.g., the ABCDEF bundle) [37], initiate early physical therapy, and closely monitor and manage various geriatric syndromes. The observed phenomenon of delayed recovery in some patients during the ward phase in our study is a clear signal that this aspect requires systematic strengthening.

From a clinical translation perspective, our findings offer preliminary guidance for surgical decision-making in this vulnerable population. For instance, in patients aged $\geq$80 years with impaired left ventricular function (e.g., LVEF $<$50%) or a history of prior myocardial infarction—subgroups that constituted a larger proportion of the on-pump cohort in this study—the choice of on-pump CABG may provide a safety advantage by ensuring hemodynamic stability during complex revascularization. Although this strategy was associated with longer initial ICU recovery, it did not compromise overall hospital stay or mid-term outcomes. Conversely, for relatively fitter very elderly patients with preserved ventricular function and fewer comorbidities, off-pump CABG may offer faster early recovery without sacrificing mid-term prognosis. These observations suggest that rather than pursuing a 'one-size-fits-all' approach, surgical technique should be tailored to individual patient risk profiles, with on-pump reserved for higher-risk anatomical and functional profiles.

Limitations of the Study

This study has several limitations that warrant cautious interpretation. First, its single-center, retrospective design with a small sample size (n = 62) limits statistical power and increases the risk of type II error, precluding formal adjustments for multiple comparisons or advanced modeling (e.g., propensity score matching).

Second, the stringent selection criteria applied at our center (surgical rate of only 0.95%) limit the external validity of the findings, as the cohort represents a highly selected, relatively healthy subset of very elderly surgical patients. However, this selectivity also defines the study's intrinsic value: it provides preliminary real-world evidence on which very elderly patients may safely benefit from CABG surgery and achieve favorable outcomes.

Finally, this study faces the inherent limitations of a retrospective, non-randomized design. Baseline imbalances in key prognostic factors (notably prior myocardial infarction and LVEF) combined with surgeon-directed treatment allocation introduce inevitable selection bias; consequently, observed differences in early recovery may partially reflect patient characteristics rather than the surgical technique alone. These findings should therefore be viewed as hypothesis-generating preliminary evidence.

Nonetheless, this study provides valuable real-world data for an understudied, high-risk population and establishes a foundation for future multicenter prospective trials incorporating comprehensive frailty assessments.

Conclusions

In this retrospective analysis of selected very elderly patients ($\geq$80 years) undergoing isolated CABG, both on-pump and off-pump techniques demonstrated comparable 30-day and one-year survival outcomes, with no statistically significant differences in major adverse cardiac and cerebrovascular events. Although off-pump CABG was associated with shorter durations of early physiological recovery—specifically reduced postoperative mechanical ventilation time and ICU length of stay—this advantage did not translate into a significant reduction in total hospital stay. Notably, postoperative stroke emerged as the predominant attributable cause of mortality throughout the first postoperative year. Given the inherent limitations of this small, non-randomized study, these findings should be interpreted as hypothesis-generating. Future prospective studies incorporating comprehensive frailty assessments are warranted to validate these observations and to develop individualized surgical strategies for this high-risk, growing population.

Availability of Data and Materials

The data analyzed are available from the corresponding author upon reasonable request.

Author Contributions

MMT contributed to study design, data analysis, writing the original manuscript, and methodology; XL contributed to study design, paper review, validation, supervision, and data curation; NWJ and JL contributed to data acquisition and data analysis. All authors have been involved in revising the manuscript critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

This study was approved by the Ethics Committee of Qilu Hospital of Shandong University (Approval No. KYLL-202308-024). All procedures involving human participants were performed in accordance with the ethical standards of the institutional and/or national research committee, the Declaration of Helsinki, and its later amendments or comparable ethical standards. Informed consent was obtained from all subjects. All information about the subjects in the article has been sufficiently anonymized.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

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