

Article

Early Outcomes and Perioperative Physiological Alterations After Isolated CABG Performed With Conventional Open Cardiopulmonary Bypass in a Limited-Resource Setting: A Retrospective Single-Center Cohort Study

Saimir Kuci¹, Federica M. Procaccini², Ermal Likaj³, Alfred Ibrahim¹, Marsela Goga¹, Verona Beka⁴, Erjola Bolleke⁵, Romina Teliti⁴, Jacob Zeitani^{2,*}

¹Anesthesiology and Reanimation Department, Mother Teresa University, 1000 Tirana, Albania

²Neurosciences and Rehabilitation Department, University of Ferrara, 44121 Ferrara, Italy

³Cardiac Surgery Department, Mother Teresa University, 1000 Tirana, Albania

⁴Department of Cardiology, German Hospital, 1001 Tirana, Albania

⁵Nephrology and Dialysis Department, Mother Teresa University, 1000 Tirana, Albania

*Correspondence: jacob.zeitani@unife.it (Jacob Zeitani)

Academic Editor: Haiyang Li

Submitted: 14 May 2026 Revised: 29 June 2026 Accepted: 2 July 2026 Published: 15 October 2026

Abstract

Background: Conventional on-pump cardiopulmonary bypass (CPB) remains widely used in coronary artery bypass grafting (CABG), particularly in limited-resource healthcare systems because of its lower upfront cost and technical simplicity. However, conventional extracorporeal circulation has been associated with systemic inflammation, hemodilution, organ dysfunction, transfusion exposure, and increased postoperative resource utilization. This study evaluated early postoperative outcomes following isolated elective CABG performed using conventional open CPB and explored potentially modifiable determinants of postoperative morbidity. **Methods:** This retrospective single-center observational study included 122 consecutive adult patients undergoing isolated elective on-pump CABG between January 2024 and March 2025. Emergency procedures, redo surgery, combined procedures, and off-pump CABG were excluded. Primary endpoints were 30-day mortality and acute kidney injury (AKI). Secondary endpoints included postoperative bleeding, postoperative atrial fibrillation (POAF), transfusion requirement, mechanical ventilation time, intensive care unit (ICU) stay, postoperative hospital stay, and re-exploration for bleeding. **Results:** Thirty-day mortality was 0%. Mean CPB time was 62.6 ± 16 minutes and mean cross-clamp time was 34.9 ± 10.1 minutes. Patients received a mean of 2.99 ± 0.64 grafts, with at least one internal mammary artery used in all cases. AKI occurred in 28.7% of patients, predominantly Kidney Disease: Improving Global Outcomes (KDIGO) stage 1. Significant perioperative hemodilution was observed, with hematocrit decreasing from 43.4% preoperatively to 32.4% on ICU admission. Mean 24-hour chest drainage was 411.8 ± 169.3 mL, while transfusion was required in 9.8% of patients. POAF occurred in 18% of cases and re-exploration for bleeding in 3.3%. Mean ventilation time was 3.4 ± 1.7 hours, ICU stay was 1.15 ± 0.44 days, and postoperative hospital stay was 6.77 ± 1.32 days. CPB duration was not significantly associated with AKI, transfusion, or POAF. However, transfusion exposure was strongly associated with prolonged ventilation and ICU stay. **Conclusions:** In this exploratory, retrospective single-center analysis without a comparator group, conventional open CPB enabled excellent short-term survival and rapid postoperative recovery when combined with efficient surgical execution and standardized perioperative care. Nevertheless, clinically significant perioperative physiological disturbances remained evident despite favorable early clinical outcomes, particularly in the form of AKI, persistent perioperative hemodilution, and transfusion-associated ICU prolongation. Favorable early clinical outcomes may coexist with measurable postoperative physiological burden, potentially increasing downstream healthcare resource utilization. Progressive implementation of goal-directed perfusion, blood conservation strategies, viscoelastic coagulation monitoring, and more biocompatible extracorporeal circulation technologies may further improve outcomes and healthcare sustainability, particularly in resource-limited settings.

Keywords: CABG; cardiopulmonary bypass; acute kidney injury; hemodilution; transfusion; systemic inflammatory response; coronary artery bypass grafting

1. Introduction

Coronary artery bypass grafting (CABG) remains one of the most effective and durable treatments for multi-vessel coronary artery disease, especially in diabetic patients [1,2]. Despite major advances in surgical technique, myocardial protection, anesthesia, and perioperative management, cardiopulmonary bypass (CPB) continues to

represent a substantial source of physiological stress during cardiac surgery. Conventional open CPB systems expose blood to artificial surfaces, air–blood interfaces, roller pump shear stress, and cardiotomy suction reinfusion [3,4]. These mechanisms may trigger systemic inflammatory activation, hemodilution, endothelial dysfunction, oxidative stress, coagulopathy, and organ injury, particularly affect-



ing renal and pulmonary function [5]. In many limited-resource healthcare systems, conventional non-coated CPB circuits remain widely used because of lower upfront cost, technical familiarity, and reduced infrastructure requirements [5,6]. However, the apparent economic advantage of conventional extracorporeal circulation may be partially offset by downstream complications such as transfusion exposure, acute kidney injury (AKI), prolonged mechanical ventilation, and increased intensive care resource utilization [7,8,9]. Importantly, contemporary CABG outcomes are increasingly influenced not only by mortality but also by perioperative physiological alterations and postoperative morbidity that may affect organ function, recovery trajectories, and healthcare resource utilization [4,6]. The aim of this study was therefore to evaluate the impact of conventional open CPB on early postoperative outcomes in a contemporary cohort of patients undergoing isolated elective CABG within a limited-resource setting and to identify potentially modifiable determinants of postoperative morbidity and hospital resource utilization. For the purpose of this study, “physiological burden” refers to measurable perioperative physiological alterations occurring despite acceptable early clinical outcomes and survival. These include perioperative hemodilution, renal functional changes assessed by serum creatinine and Kidney Disease: Improving Global Outcomes (KDIGO)-defined acute kidney injury, and postoperative recovery indicators such as transfusion exposure, duration of mechanical ventilation, and intensive care unit (ICU) stay.

2. Methods

2.1 Study Design and Population

This retrospective observational single-center cohort study included 122 consecutive adult patients undergoing isolated elective on-pump CABG at a tertiary cardiac surgery center. To ensure cohort homogeneity, patients undergoing emergency surgery, redo sternotomy, combined procedures, or off-pump CABG were excluded. Patients receiving clopidogrel within 5 days before surgery also were excluded. The preoperative characteristics of the patients are shown in Table 1. All procedures were performed by the same dedicated cardiac surgery team, including surgeons, anesthesiologists, and perfusionists, using standardized intraoperative and perioperative protocols.

2.2 Surgical and Perfusion Management

All surgical procedures, after skin preparation with povidone-iodine solution and the administration of preoperative antibiotics (1 intravenous ceftizoxime) before incision, were performed through median sternotomy, aortic and bicaval cannulation, using conventional open non-heparin-coated CPB circuits with crystalloid priming and standard roller pump systems. Direct cardiectomy suction reinfusion was routinely used. Systemic anticoagulation was achieved using unfractionated heparin with protamine

Table 1. Preoperative patient characteristics.

Characteristics	Value	Range (min–max)
Age (years)	64 ± 8.7	28–83
Preoperative hematocrit (%)	43.4 ± 4.4	26.7–51
Preoperative serum creatinine (mg/dL)	0.99 ± 0.23	0.58–1.9
Preoperative ejection fraction (%)	54 ± 8	25–65
BMI, kg/m ²	26.7 ± 1.6	25–34
CCS	2.3 ± 1.0	1–4
NYHA class	2 ± 1.0	I–III
Hyperlipidemia (n)	48 (39)	–
Diabetes mellitus (n)	65 (53)	–
COPD (n)	52 (43)	–
Smoking habit (n)	98 (80)	–

Data are presented as mean ± standard deviation or number (%). BMI, body mass index; CCS, canadian cardiovascular society; COPD, chronic obstructive pulmonary disease; NYHA, new york heart association.

reversal at a 1:1 ratio according to institutional protocol. Myocardial protection was achieved using intermittent tepid blood cardioplegia, repeated every 20–25 min. Mild systemic hypothermia (32–33 °C) was maintained during CPB. Routine hemoconcentration, modified ultrafiltration, viscoelastic coagulation monitoring Rotational thromboelastometry (ROTEM) or Thromboelastography (TEG), and goal-directed oxygen delivery monitoring were not available in the institutional practice setting during the study period. To characterize the physiological effects of perfusion, perioperative laboratory measurements including hemoglobin, hematocrit, and serum creatinine were collected serially. Recorded intraoperative variables included number of distal grafts, CPB duration, aortic cross-clamp time, and minimum CPB temperature (Table 2).

Table 2. Intraoperative characteristics.

Characteristics	Value	Range (min–max)
Number of bypass grafts	2.99 ± 0.64	2–4
Cardiopulmonary bypass time (min)	62.6 ± 16	30–101
Aortic cross-clamp time (min)	34.9 ± 10.1	17–58
Minimum CPB temperature (°C)	32.1 ± 0.3	32–33

Data are presented as mean ± standard deviation. CPB, cardiopulmonary bypass.

2.3 Anesthetic and Postoperative Management

A standardized fast-track cardiac anesthesia protocol was applied to all patients with the objective of early extubation and rapid ICU discharge. Postoperative management included invasive hemodynamic monitoring, early ventilatory weaning, and empirical transfusion management based on conventional laboratory testing and clinical assessment. In particular, red blood cell transfusion was generally con-

sidered for hemoglobin values below 7 g/dL or below 8 g/dL and Haematocrit (Hct) <24%, in clinically unstable patients or in the presence of ongoing bleeding, impaired oxygen delivery, or significant hemodynamic compromise. Routine viscoelastic coagulation monitoring and protocolized transfusion algorithms were not available. Inotropic and vasoactive support was administered according to clinical need.

2.4 Data Collection

Clinical, intraoperative, laboratory, and postoperative data were retrospectively extracted from institutional databases. Collected variables included demographic characteristics, baseline comorbidities, operative variables, transfusion requirements, postoperative complications, ventilation time, ICU stay, hospital length of stay, and laboratory parameters including hemoglobin, hematocrit, and serum creatinine. Institutional Ethics Committee approval was obtained. The study was approved by the Ethics Committee of The German Hospital, Tirana (Protocol No. 22058/25). Because this retrospective study analyzed existing anonymized medical records, the requirement for informed consent was waived by the Institutional Review Board.

2.5 Study Endpoints

Primary endpoints were 30-day mortality and AKI. Secondary endpoints included postoperative bleeding, transfusion requirement, mechanical ventilation duration, postoperative atrial fibrillation (POAF), ICU length of stay, total postoperative hospitalization, and re-exploration for bleeding.

AKI was defined according to the KDIGO criteria based on serum creatinine changes [10]. Stage 1 was defined as an increase in serum creatinine ≥ 0.3 mg/dL within 48 hours or 1.5–1.9 times baseline within 7 days. Stage 2 was defined as an increase to 2.0–2.9 times baseline. Stage 3 was defined as an increase to ≥ 3 times baseline, serum creatinine ≥ 4.0 mg/dL, or requirement for renal replacement therapy. POAF was defined as any documented episode of atrial fibrillation occurring during postoperative hospitalization and detected either by continuous bedside ECG monitoring or confirmation on standard 12-lead electrocardiography. Continuous rhythm monitoring was maintained throughout ICU stay, followed by routine clinical and electrocardiographic surveillance after transfer to the ward. Management was performed according to institutional practice, predominantly using intravenous amiodarone.

2.6 Statistical Analysis

Continuous variables are presented as mean $\pm$ standard deviation (SD), while categorical variables are presented as percentages.

Normality distribution was assessed before analysis. Comparisons between groups were performed using Student's *t*-test or Mann–Whitney U test according to data distribution. Categorical variables were compared using chi-square or Fisher's exact test.

Correlation analyses were performed using Pearson or Spearman coefficients as appropriate. A *p*-value < 0.05 was considered statistically significant. Additional multivariable logistic regression analyses were performed to identify independent predictors of postoperative AKI, transfusion requirement, and POAF. Candidate variables were selected based on clinical plausibility and statistical relevance while respecting event-per-variable considerations to reduce model overfitting. Regression results were reported using regression coefficients (β), odds ratios (ORs), and corresponding significance statistics where appropriate. However, no Receiver Operating Characteristic (ROC)-based predictive modeling, interaction testing, or sensitivity analyses were performed, as the study was not designed for model derivation or validation. This retrospective study included all consecutive eligible patients during the study period. No formal a priori sample size calculation was performed because no interventional comparison or predefined hypothesis-testing model was planned. Therefore, all statistical analyses should be considered exploratory in nature.

3. Results

3.1 Baseline and Intraoperative Characteristics

The cohort had a mean age of 64 ± 8.7 years and was predominantly male (78.7%) (Fig. 1). Sixty-five and ninety-eight patients presented with Diabetes Mellitus and smoking history, respectively. Ninety-three patients had three vessels coronary artery disease (76%) and 29 patients had two-vessel coronary artery disease. Patients underwent a mean of 2.99 ± 0.64 distal grafts, with the left internal mammary artery (LIMA) used to revascularize the left anterior descending artery (LAD) in all patients, reflecting a relatively complex burden of coronary artery disease. Mean CPB duration was 62.6 ± 16 minutes, while mean aortic cross-clamp time was 34.9 ± 10.1 minutes. Intraoperative data are reported in Table 2.

3.2 Early Postoperative Outcomes

Thirty-day mortality was 0%. Mean 24-hour chest drainage was 411.8 ± 169.3 mL. Allogeneic transfusion was required in 12 patients (9.8%). Mean mechanical ventilation time was 3.4 ± 1.7 hours. Mean ICU stay was 1.15 ± 0.64 days, while mean postoperative hospital stay was 6.77 ± 1.32 days. POAF occurred in 23 patients (18.8%). Re-exploration for bleeding was required in 4 patients (3.3%). AKI occurred in 35 patients (28.7%). Postoperative data are reported in Table 3. According to KDIGO classification, 24 patients (68.5%) developed stage 1 AKI, 7 patients (20.0%) developed stage 2 AKI, and 4 patients (11.5%) developed

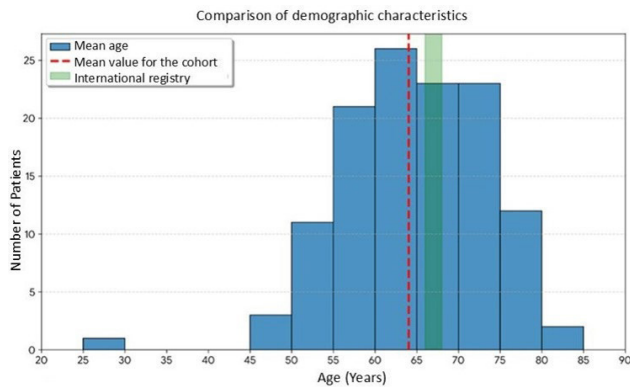


Fig. 1. Comparison of demographic characteristics. Blue bars represent the age distribution of the study cohort (mean: 64 years; range: 28–83 years). The vertical red dashed line indicates the mean age for the study cohort, and the green shaded band represents the reference range/mean from an international registry (66–68 years).

stage 3 AKI, indicating that most cases represented mild renal dysfunction. Serum creatinine increased significantly from 0.99 ± 0.23 mg/dL preoperatively to 1.12 mg/dL postoperatively ($p < 0.001$). Despite excellent short-term clinical outcomes, measurable perioperative physiological perturbations were observed. Hematocrit decreased substantially following cardiopulmonary bypass, with values declining from 43.4% preoperatively to 32.4% on ICU arrival (Fig. 2). This reduction in hematocrit and hemoglobin was interpreted as an indirect indicator of perioperative hemodilution within the context of the institutional perfusion strategy, although direct perfusion-derived hemodilution indices were not available. A subset of patients required transfusion and experienced prolonged ventilation and ICU stay.

Table 3. Postoperative outcomes data.

Parameter	Value	Range (min–max)
24-hour postoperative bleeding (mL)	411.8 ± 169.3	110–800
Mechanical ventilation time (hours)	3.4 ± 1.7	1–12
ICU length of stay (days)	1.15 ± 0.44	1–3
Total postoperative hospital stay (days)	6.77 ± 1.32	5–13
Allogeneic transfusion rate (n)	12 (9.8)	–
AKI	35 (28.7)	–
POAF	23 (18.8)	–
30-day mortality	0%	–

Data are presented as mean $\pm$ standard deviation or number. Abbreviations: ICU, intensive care unit; AKI, acute kidney injury; POAF, postoperative atrial fibrillation.

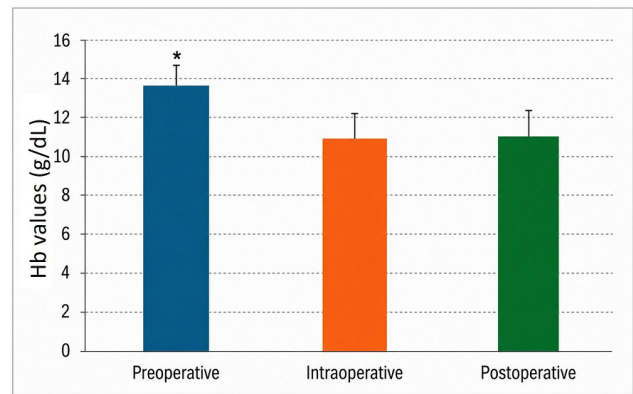


Fig. 2. The trend in mean hemoglobin (Hb) values across the three perioperative phases demonstrated a significant reduction between preoperative and intraoperative measurements (* $p < 0.001$).

3.3 Determinants of Postoperative Recovery

CPB duration was not significantly associated with AKI (Fig. 3), transfusion requirement, or POAF. Increased postoperative chest drainage demonstrated a significant positive correlation with delayed extubation time ($p = 0.031$) (Fig. 4). Patients requiring transfusion demonstrated significantly prolonged ventilation duration and ICU stay (ICU stay: 1.70 vs 1.10 days; $p < 0.001$). A strong positive correlation was observed between ventilation time and ICU length of stay ($r = 0.5$; $p < 0.001$). Obese patients demonstrated significantly faster extubation compared with non-obese patients (3.56 vs 4.17 hours; $p = 0.04$), consistent with the obesity paradox described in cardiac surgery literature. Inotropic support using adrenaline was required during CPB separation in 27.8% of patients, although prolonged support beyond 24 hours was rare. Multivariable logistic regression analyses were performed to evaluate independent predictors of postoperative AKI, transfusion requirement, and POAF. Candidate variables included age, preoperative hematocrit, diabetes mellitus, obesity, preoperative serum creatinine, CPB duration, and cross-clamp time. For postoperative AKI, the multivariable model demonstrated overall statistical significance ($\Delta\chi^2 = 51.87$, $p < 0.001$; McFadden $R^2 = 0.356$; Nagelkerke $R^2 = 0.498$). Within this model, only preoperative serum creatinine was independently associated with AKI ($p < 0.001$). In the raw statistical software output matrix, the default baseline reference category configuration yielded inverted directional parameters ($\beta = -9.578$; OR = 6.927×10^{-5}). Because the underlying clinical data and absolute Wald metrics confirm that elevated baseline renal function represents a significant risk factor rather than a protective element, these parameters have been mathematically rectified ($\beta = +9.578$; OR = 14,443.3) in this final report to accurately reflect the true positive risk direction relative to the occurrence of AKI. No independent associations were identified for age, preoperative hematocrit, diabetes mellitus, obesity, CPB duration, or

Table 4. Multivariable logistic regression analysis for postoperative outcomes.

Variable	β (Estimate)	SE	z	p-value	OR (Exp β)	Interpretation
Intercept	6.952	3.057	2.274	0.023	1048.0	baseline
Age	-0.007	0.036	-0.183	0.855	0.993	NS
Hct preop	-0.004	0.027	-0.142	0.887	0.996	NS
DM	0.345	0.539	0.641	0.521	1.412	NS
Obesity	-0.435	0.662	-0.656	0.512	0.647	NS
Creatinine (mg/dL) ^{a,*}	+9.578	1.924	+4.978	<0.001	14,443.3	
CPB (min)	0.014	0.032	0.444	0.657	1.014	NS
Cross-clamp	0.016	0.050	0.322	0.747	1.016	NS

Abbreviations: AKI, acute kidney injury; OR, odds ratio; DM, diabetes mellitus; KDIGO, kidney disease: improving global outcomes; CPB, cardiopulmonary bypass; NS, non-significant. AKI was coded as KDIGO stage ≥ 1 vs no AKI. ^aPostoperative AKI was modeled as the primary binary dependent outcome (1 = AKI vs 0 = No AKI). Preoperative serum creatinine was analyzed as a continuous numerical variable (mg/dL). The reported positive regression coefficient (β) and corresponding Odds Ratio (OR) have been aligned to reflect the positive risk association relative to the occurrence of AKI. *Statistically significant.

cross-clamp time. For transfusion requirement and POAF, multivariable models did not demonstrate overall statistical significance (transfusion: $\Delta\chi^2 = 7.18$, $p = 0.410$; POAF: $\Delta\chi^2 = 4.65$, $p = 0.703$), and no independent predictors were identified. Detailed regression results are presented in Tables 4,5.

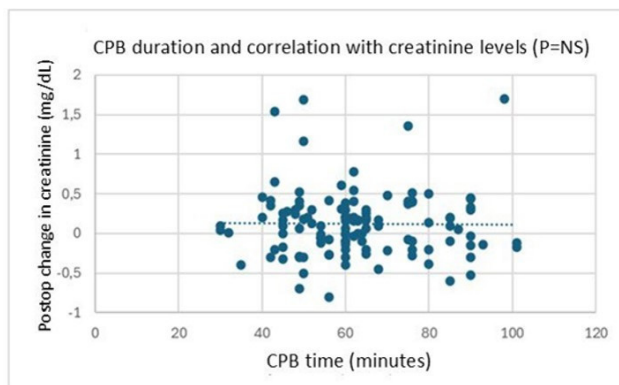


Fig. 3. Relationship between standard CPB duration (minutes) and postoperative increase in serum creatinine (mg/dL). Within the perfusion times recorded in the study cohort, no linear correlation with organ injury was observed.

4. Discussion

This study demonstrates that conventional open cardiopulmonary bypass can provide excellent short-term safety in isolated elective CABG when combined with efficient surgical execution, short operative times, standardized anesthetic protocols, and coordinated perioperative care. However, one of the major postoperative endpoints, AKI, occurred in 35 patients (28.7%), predominantly corresponding to KDIGO stage 1 injury, resulting in a significant postoperative increase in serum creatinine levels. Several con-

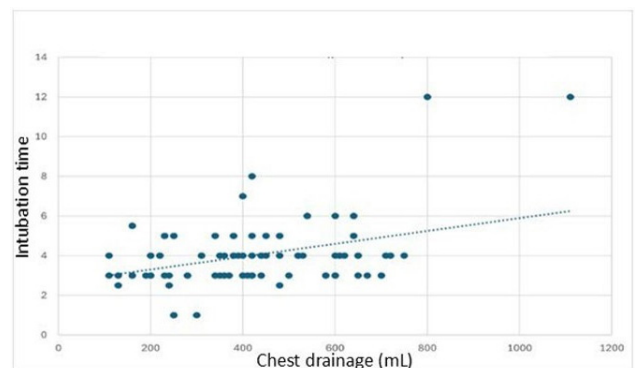


Fig. 4. Correlation between postoperative chest drain (mL) and intubation time ($\rho = 0.196$, $p = 0.031$). Increased postoperative blood loss significantly delays extubation.

sensus definitions have been developed to standardize the diagnosis of AKI. In 2004, the Acute Dialysis Quality Initiative (ADQI) group introduced the RIFLE classification, categorizing renal dysfunction into Risk, Injury, Failure, Loss, and End-stage Kidney Disease. Subsequently, the Acute Kidney Injury Network (AKIN) refined these criteria, and more recently the KDIGO workgroup integrated both systems into a unified and more comprehensive definition of AKI [10].

Table 5. Multivariable model performance.

Outcome	$\Delta\chi^2$	p value	McFadden R^2	Nagelkerke R^2
AKI	51.87	<0.001*	0.356	0.498
Transfusion	7.18	0.410	0.122	0.150
POAF	4.65	0.703	0.041	0.064

Abbreviations: AKI, acute kidney injury; POAF, postoperative atrial fibrillation; $\Delta\chi^2$, likelihood ratio chi-square statistic. *Statistically significant.

The most relevant finding of the present study is the apparent discordance between excellent early clinical outcomes and the persistence of a clinically relevant perioperative physiological disturbances despite favorable early recovery. Despite zero 30-day mortality and rapid postoperative recovery, AKI occurred in nearly one-third of patients. Importantly, no significant association was identified between AKI and traditional baseline risk factors such as diabetes mellitus, smoking, chronic kidney disease, or CPB duration, suggesting that perioperative and CPB-related physiological mechanisms may have contributed to the observed postoperative renal dysfunction, although causality cannot be established within the present study design. Conventional CPB circuits expose blood to multiple non-physiological conditions, including artificial surfaces, air-blood interfaces, roller pump shear stress, and cardiectomy suction-related hemolysis. These mechanisms promote systemic inflammatory activation, endothelial dysfunction, oxidative stress, and microcirculatory injury, all of which may contribute to renal impairment despite preserved macro-hemodynamic stability. A likely additional contributor was oxygen delivery debt during CPB. Contemporary perfusion literature consistently demonstrates that inadequate indexed oxygen delivery significantly increases postoperative AKI risk. The development of AKI after CABG is influenced by multiple perioperative factors including cardiopulmonary bypass duration, prolonged aortic cross-clamp time, and low cardiac output states, all of which may impair renal perfusion and promote inflammatory-mediated renal injury. Previous studies demonstrated a significant association between prolonged CPB exposure and postoperative AKI [11,12]. In the present study, however, both CPB and cross-clamp times were relatively short, which may have contributed to limiting the severity of renal dysfunction observed, despite the relatively high incidence of predominantly mild KDIGO stage 1 AKI. Importantly, the majority of AKI cases were limited to KDIGO stage 1 injury, suggesting predominantly subclinical or transient renal dysfunction rather than severe postoperative renal failure. Persistent perioperative hemodilution represented another important finding. Although controlled hemodilution during cardiopulmonary bypass, particularly under hypothermic conditions, is an established and often beneficial strategy to reduce blood viscosity and support microcirculatory perfusion, persistent postoperative hemodilution may have less favorable effects. In our cohort, large crystalloid priming volumes likely contributed to sustained reductions in hematocrit, interstitial fluid accumulation, impaired pulmonary compliance, and delayed respiratory recovery [12,13,14,15,16]. Although transfusion rates remained relatively low, transfusion exposure was strongly associated with prolonged mechanical ventilation and ICU stay, highlighting the substantial organizational and economic burden associated with blood product administration. Similarly, the relatively frequent requirement for adrenaline support

during weaning from CPB likely reflects transient vasoplegia and myocardial stunning associated with inflammatory activation and nonphysiological extracorporeal circulation [17,18]. Importantly, this study also highlights the protective impact of surgical efficiency and coordinated multidisciplinary perioperative management. Short CPB and cross-clamp times likely mitigated part of the inflammatory and ischemic burden associated with conventional perfusion systems and contributed substantially to the excellent overall outcomes observed. Despite these limitations, the inclusion of consecutive patients reflects routine clinical practice and provides real-world insight into CABG outcomes in a limited-resource environment.

Contemporary CABG populations increasingly present with multiple systemic comorbidities and more complex coronary anatomy, amplifying perioperative vulnerability and the physiological impact of cardiopulmonary bypass. This evolving clinical profile may partially explain the persistent incidence of postoperative complications such as AKI, POAF, prolonged ventilation, and transfusion-related morbidity despite technically successful surgical revascularization [19,20].

Consequently, optimization of extracorporeal circulation strategies and perioperative organ protection has become increasingly important not only for improving clinical outcomes but also for reducing the organizational and economic burden associated with contemporary cardiac surgical care.

The growing interest in off-pump coronary artery bypass (OPCAB) surgery has largely been driven by the intention to avoid the inflammatory and organ-related complications associated with conventional cardiopulmonary bypass [21,22,23]. However, in the contemporary Percutaneous Coronary Intervention (PCI) era, patients referred for surgical revascularization increasingly represent a more complex and higher-risk subgroup requiring multiple grafts and complete revascularization [23]. Therefore, while OPCAB may reduce CPB-related physiological injury in selected patients, conventional extracorporeal circulation continues to play a central role in achieving optimal surgical completeness in complex modern CABG populations.

4.1 Implications for Limited-Resource Healthcare Systems

The findings of this study acquire particular relevance within low- and middle-income healthcare systems, where limitations in perfusion technology, infrastructure, and perioperative monitoring frequently restrict implementation of advanced extracorporeal circulation strategies. Although conventional open CPB systems remain attractive because of lower upfront costs and logistical simplicity, the present analysis suggests that downstream complications including AKI, transfusion exposure, prolonged ventilation, and increased ICU utilization may partially offset the apparent economic advantage of basic perfusion systems, as postoperative AKI and perioperative complications have been

shown to markedly increase hospitalization costs and resource utilization after cardiac surgery [7,8]. These complications generate additional institutional costs through increased blood product consumption, prolonged critical care occupancy, delayed discharge, and perioperative re-interventions. Consequently, targeted technological upgrading should be viewed not as luxury expenditure but as value-based reinvestment. Practical and scalable improvement strategies may include: viscoelastic point-of-care hemostatic monitoring; individualized protamine titration; routine cell salvage; modified ultrafiltration; goal-directed perfusion targeting adequate oxygen delivery; progressive adoption of minimally invasive extracorporeal circulation (MiECC); optimization of pharmacologic unloading strategies.

Cost-effectiveness and sustainability: cost-benefit analysis of technological upgrade in a resource-limited healthcare system.

In healthcare systems characterized by limited resources, economic decisions are often driven by the need to reduce immediate expenditure. However, modern health economics requires moving beyond the simple evaluation of the purchase price of a device or drug toward an assessment of the total cost of care throughout the entire perioperative course.

The magnitude of these costs has been quantified in large-scale analyses from the Society of Thoracic Surgeons (STS) database involving more than 36,000 patients, showing that the average cost of an uncomplicated CABG procedure is approximately 36,580 USD, whereas the occurrence of major postoperative complications leads to an exponential increase in healthcare expenditure, generating a multimillion-dollar economic burden over time [24]. The findings of the present study objectively demonstrate how the apparent initial savings associated with lower-cost technologies are subsequently offset during the postoperative phase: Prolonged ICU stay: patients receiving allogeneic blood transfusions experienced a significantly longer ICU stay ($p < 0.001$). Economic analyses of postcardiac surgery critical care have shown that ICU hospitalization represents one of the most expensive components of the entire treatment pathway. The cost of a single ICU day for mechanically ventilated patients may exceed 10,000 USD during the first 24 hours and remain around 4000 USD for each additional day, with substantially higher costs compared with non-ventilated patients [25]. Reoperation for bleeding: 3.3% of patients required surgical re-exploration for hemostasis. Emergency reopening of the operating room dramatically increases hospital costs and resource utilization, representing a major economic burden for cardiac surgery programs [24]. Management of organ complications: the 28.7% incidence of postoperative AKI observed in the cohort required prolonged medical treatment and specialist care. Postoperative renal dysfunction is among the most resource-consuming complications in cardiac surgery

and has been associated with markedly increased mortality, ventilation time, ICU stay, prolonged hospitalization, and a near doubling of total hospitalization costs [8,25]. Against this background, the implementation of advanced technologies such as viscoelastic coagulation monitoring (ROTEM), MiECC, and enoximone should be regarded not as additional expenses, but as long-term structural investments. The cost-effectiveness of ROTEM-guided transfusion strategies has been consistently demonstrated in the international literature. Although the acquisition of the device and reagents represents an initial fixed investment, targeted transfusion protocols significantly reduce the use of packed red blood cells, fresh frozen plasma, and platelets. Spalding et al. [26], in a cohort of more than 1400 cardiac surgery patients, reported a 50% reduction in platelet concentrate utilization and a 25% reduction in red blood cell transfusions following ROTEM implementation. Importantly, monthly blood product expenditure decreased by approximately 44%, generating substantial net savings that rapidly compensated for the cost of the technology itself [26].

Similarly, despite the higher acquisition cost of disposable MiECC circuits compared with conventional extracorporeal circulation systems, modern macroeconomic analyses identify MiECC as a “dominant strategy”, meaning that it simultaneously improves clinical outcomes while reducing overall healthcare costs. European analyses demonstrated that reductions in postoperative complications, transfusion requirements, ICU stay, and resource utilization translated into overall savings ranging from approximately 300 to 1600 euros per procedure. Therefore, the initial investment required for MiECC is largely offset by improved postoperative recovery and reduced resource consumption [7].

Finally, although enoximone is more expensive than traditional catecholamine therapy on a per-dose basis, its pharmacological profile may contribute to improved hemodynamic stability, reduced inflammatory response, lower incidence of arrhythmias, and facilitation of fast-track recovery protocols. By shortening ICU stay and accelerating postoperative recovery, the initial pharmacological expenditure may ultimately translate into overall economic savings.

In conclusion, in resource-limited healthcare systems, technological and pharmacological upgrading of extracorporeal circulation should not be considered an unjustified expense, but rather a strategic investment capable of aligning surgical excellence with long-term economic sustainability.

4.2 Limitations

This study is limited by its retrospective single-center design and absence of a comparator group using modern perfusion technologies. Consequently, the observed outcomes cannot be directly attributed to conventional car-

diopulmonary bypass itself, and causal relationships between CPB-related factors and postoperative outcomes cannot be established. The findings should therefore be interpreted as descriptive associations within a standardized conventional perfusion strategy rather than comparative evidence of superiority or direct causation. The study population was restricted to elective isolated CABG procedures, which enhances internal consistency but may limit the external generalizability of the findings to higher-risk populations such as emergency surgery, redo operations, or combined cardiac procedures. Continuous intraoperative monitoring of oxygen delivery, lactate kinetics, inflammatory biomarkers, and viscoelastic coagulation parameters was not available, limiting mechanistic interpretation. Renal reserve was not comprehensively characterized using advanced preoperative renal function testing. Nevertheless, the study provides realistic insight into CABG outcomes achieved using conventional perfusion systems within a limited-resource environment. Finally, the relatively modest cohort size may have limited the ability to detect smaller effect sizes and restricted the robustness of adjusted statistical modeling. Although multivariable logistic regression analyses were performed, the exploratory nature of the study and limited number of outcome events may have reduced model stability. ROC-based predictive analysis, interaction testing, and sensitivity analyses were not performed because the study was not designed for model derivation or validation. Therefore, findings should be interpreted as exploratory associations rather than predictive or causal relationships.

5. Conclusions

Within the limitations of a retrospective single-center design lacking a comparative cohort, excellent surgical execution and standardized perioperative care coexisted with outstanding short-term survival despite the use of conventional open cardiopulmonary bypass systems. However, significant subclinical physiological burden persists, particularly in the form of acute kidney injury, perioperative hematologic and fluid balance disturbances (including non-physiological or excessive hemodilution), transfusion-associated ICU prolongation, and postoperative inflammatory burden. Future improvements in CABG outcomes may therefore depend less on further reductions in operative times and more on targeted reduction of CPB-related physiological injury through optimized perfusion strategies, enhanced blood conservation, goal-directed hemostatic management, and progressive adoption of more biocompatible extracorporeal circulation technologies. Even incremental technological investments may provide substantial clinical and economic benefit in resource-constrained healthcare systems.

Availability of Data and Materials

The datasets generated and analyzed during the current study are not publicly available due to patient privacy and data protection restrictions, but are available from the corresponding author upon reasonable request.

Author Contributions

SK, FMP, EL, AI, MG, VB, EB, RT, and JZ all made substantial contributions to conception and design as well as acquisition and interpretation of data. FMP, SK, EL, VB, EB, RT and MG contributed to writing the first draft and collected all pts data. FMP, EL, AI, SK, MG, and JZ were involved in drafting the manuscript or reviewing it critically for important intellectual content and supervised the whole process. All authors contributed to editorial changes in the manuscript. All authors gave final approval of the version to be published and take public responsibility for appropriate portions of the content and are accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was carried out in accordance with the guidelines of the Declaration of Helsinki. The study was approved by the Ethics Committee of The German Hospital, Tirana (Protocol No. 22058/25). Because this retrospective study analyzed existing anonymized medical records, the requirement for informed consent was waived by the Institutional Review Board.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Farkouh ME, Domanski M, Sleeper LA, Siami FS, Dangas G, Mack M, et al. Strategies for multivessel revascularization in patients with diabetes. *The New England Journal of Medicine*. 2012; 367: 2375–2384. <https://doi.org/10.1056/NEJMoa1211585>
- [2] Lawton JS, Tamis-Holland JE, Bangalore S, Bates ER, Beckie TM, Bischoff JM, et al. 2021 ACC/AHA/SCAI Guideline for Coronary Artery Revascularization: A Report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. *Circulation*. 2022; 145: e18–e114. <https://doi.org/10.1161/CIR.0000000000001038>
- [3] Awad AK, Sharma A, Tang A, Alshneikat M, Koprivanac MJ, Elgharably H, et al. Postoperative Management of Patients Undergoing Coronary Artery Bypass Grafting. *Heart Surgery Forum*. 2026; 29. <https://doi.org/10.31083/HSF50271>
- [4] Shaefi S, Mittel A, Loberman D, Ramakrishna H. Off-Pump Versus On-Pump Coronary Artery Bypass Grafting-A Systematic Review and Analysis of Clinical Outcomes. *Journal of Car-*

- diathoracic and Vascular Anesthesia. 2019; 33: 232–244. <https://doi.org/10.1053/j.jvca.2018.04.012>
- [5] Wahba A, Kunst G, De Somer F, Agerup Kildahl H, Milne B, Kjellberg G, et al. 2024 EACTS/EACTAIC/EBOP Guidelines on cardiopulmonary bypass in adult cardiac surgery. *European Journal of Cardio-Thoracic Surgery*. 2025; 67: ezae354. <https://doi.org/10.1093/ejcts/ezae354>
 - [6] Zeitani J, Buccisano F, Nardella S, Flaminio M, Prati P, Chiariello G, et al. Mini-extracorporeal circulation minimizes coagulation abnormalities and ameliorates pulmonary outcome in coronary artery bypass grafting surgery. *Perfusion*. 2013; 28: 298–305. <https://doi.org/10.1177/0267659113478322>
 - [7] Anastasiadis K, Fragoulakis V, Antonitsis P, Maniadakis N. Coronary artery bypass grafting with minimal versus conventional extracorporeal circulation; an economic analysis. *International Journal of Cardiology*. 2013; 168: 5336–5343. <https://doi.org/10.1016/j.ijcard.2013.08.006>
 - [8] Alshaikh HN, Katz NM, Gani F, Nagarajan N, Canner JK, Kacker S, et al. Financial Impact of Acute Kidney Injury After Cardiac Operations in the United States. *The Annals of Thoracic Surgery*. 2018; 105: 469–475. <https://doi.org/10.1016/j.athoracsur.2017.10.053>
 - [9] Tolpin DA, Collard CD, Lee VV, Virani SS, Allison PM, Elayda MA, et al. Subclinical changes in serum creatinine and mortality after coronary artery bypass grafting. *The Journal of Thoracic and Cardiovascular Surgery*. 2012; 143: 682–688.e1. <https://doi.org/10.1016/j.jtcvs.2011.09.044>
 - [10] Kellum JA, Lameire N, KDIGO AKI Guideline Work Group. Diagnosis, evaluation, and management of acute kidney injury: a KDIGO summary (Part 1). *Critical Care*. 2013; 17: 204. <https://doi.org/10.1186/cc11454>
 - [11] Ranucci M, Di Dedda U, Cotza M, Zamalloa Moreano K. The multifactorial dynamic perfusion index: A predictive tool of cardiac surgery associated acute kidney injury. *Perfusion*. 2024; 39: 201–209. <https://doi.org/10.1177/02676591221137033>
 - [12] Wang R, Wang X, Zhu Y, Chen W, Li L, Chen X. Acute kidney injury following on-pump or off-pump coronary artery bypass grafting in elderly patients: a retrospective propensity score matching analysis. *Journal of Cardiothoracic Surgery*. 2020; 15: 186. <https://doi.org/10.1186/s13019-020-01226-8>
 - [13] Wang Z, Ge M, Wang Z, Chen C, Lu L, Zhang L, et al. Identification of risk factors for postoperative stage 3 acute kidney injury in patients who received surgical repair for acute type A aortic dissection. *BMC Surgery*. 2022; 22: 75. <https://doi.org/10.1186/s12893-022-01526-x>
 - [14] Raphael J, Chae A, Feng X, Shotwell MS, Mazzeffi MA, Bollen BA, et al. Red Blood Cell Transfusion and Pulmonary Complications: The Society of Thoracic Surgeons Adult Cardiac Surgery Database Analysis. *The Annals of Thoracic Surgery*. 2024; 117: 839–846. <https://doi.org/10.1016/j.athoracsur.2023.12.012>
 - [15] Palomba H, Trembl RE, Caldonazo T, Katayama HT, Gomes BC, Malbouisson LMS, et al. Intraoperative fluid balance and cardiac surgery-associated acute kidney injury: a multicenter prospective study. *Brazilian Journal of Anesthesiology*. 2022; 72: 688–694. <https://doi.org/10.1016/j.bjane.2022.07.006>
 - [16] Scurt FG, Bose K, Mertens PR, Chatzikyrkou C, Herzog C. Cardiac Surgery-Associated Acute Kidney Injury. *Kidney360*. 2024; 5: 909–926. <https://doi.org/10.34067/KID.0000000000000466>
 - [17] Datt V, Wadhwani R, Sharma V, Virmani S, Minhas HS, Malik S. Vasoplegic syndrome after cardiovascular surgery: A review of pathophysiology and outcome-oriented therapeutic management. *Journal of Cardiac Surgery*. 2021; 36: 3749–3760. <https://doi.org/10.1111/jocs.15805>
 - [18] Squicciarino E, Lorusso R, Consiglio A, Labriola C, Haumann RG, Piancone F, et al. Impact of Inflammation After Cardiac Surgery on 30-Day Mortality and Machine Learning Risk Prediction. *Journal of Cardiothoracic and Vascular Anesthesia*. 2025; 39: 683–691. <https://doi.org/10.1053/j.jvca.2024.12.013>
 - [19] Xiao Y, Zhao C, Xu J, Pan G. Fluid Balance and Risk of Postoperative Atrial Fibrillation after On-pump Coronary Artery Bypass Grafting Surgery. *Heart Surgery Forum*. 2024; 27: 789–796. <https://doi.org/10.59958/hsf.7661>
 - [20] Zheng XM, Yang Z, Yang GL, Huang Y, Peng JR, Wu MJ. Lung injury after cardiopulmonary bypass: Alternative treatment prospects. *World Journal of Clinical Cases*. 2022; 10: 753–761. <https://doi.org/10.12998/wjcc.v10.i3.753>
 - [21] Sun L, Zhou M, Ji Y, Wang X, Wang X. Off-pump versus on-pump coronary artery bypass grafting for octogenarians: A meta-analysis involving 146 372 patients. *Clinical Cardiology*. 2022; 45: 331–341. <https://doi.org/10.1002/clc.23794>
 - [22] Puskas JD, Martin J, Cheng DCH, Benussi S, Bonatti JO, Diegeler A, et al. ISMICS Consensus Conference and Statements of Randomized Controlled Trials of Off-Pump Versus Conventional Coronary Artery Bypass Surgery. *Innovations: Technology and Techniques in Cardiothoracic and Vascular Surgery*. 2015; 10: 219–229. <https://doi.org/10.1097/IMI.0000000000000184>
 - [23] He L, Tiemuerniyazi X, Chen L, Yang Z, Huang S, Nan Y, et al. Clinical outcomes of on-pump versus off-pump coronary-artery bypass surgery: a meta-analysis. *International Journal of Surgery*. 2024; 110: 5063–5070. <https://doi.org/10.1097/JS9.0000000000001481>
 - [24] Mehaffey JH, Hawkins RB, Byler M, Charles EJ, Fonner C, Kron I, et al. Cost of individual complications following coronary artery bypass grafting. *The Journal of Thoracic and Cardiovascular Surgery*. 2018; 155: 875–882.e1. <https://doi.org/10.1016/j.jtcvs.2017.08.144>
 - [25] Dasta JF, McLaughlin TP, Mody SH, Piech CT. Daily cost of an intensive care unit day: the contribution of mechanical ventilation. *Critical Care Medicine*. 2005; 33: 1266–1271. <https://doi.org/10.1097/01.ccm.0000164543.14619.00>
 - [26] Spalding GJ, Hartrumpf M, Sierig T, Oesberg N, Kirschke CG, Albes JM. Cost reduction of perioperative coagulation management in cardiac surgery: value of “bedside” thrombelastography (ROTEM). *European Journal of Cardio-Thoracic Surgery*. 2007; 31: 1052–1057. <https://doi.org/10.1016/j.ejcts.2007.02.022>