

Free LIMA Graft with Proximal Aortic Anastomosis for Intraoperative Proximal LIMA Injury: Short- and Mid-Term Outcomes of a Conduit-Preserving Salvage Strategy

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ABSTRACT

Background: The left internal mammary artery (LIMA) is the gold-standard conduit for left anterior descending (LAD) coronary revascularization. Proximal LIMA injury during harvest is a rare but technically challenging complication that may result in loss of the optimal arterial conduit. We evaluated the feasibility, safety, and short- to mid-term outcomes of a conduit-preserving salvage strategy using free LIMA grafting with proximal anastomosis to the ascending aorta. **Methods:** A retrospective analysis of a prospectively maintained multicenter registry was conducted across four high-volume cardiac centers between January 2018 and December 2021. Patients undergoing coronary artery bypass grafting (CABG) complicated by intraoperative proximal LIMA injury ($\geq 50\%$ transection, critical stenosis, or pedicle avulsion) were included. Salvage was performed by converting the LIMA into a free graft, with proximal anastomosis to the ascending aorta and distal anastomosis to the LAD. Intraoperative graft flow was assessed using transit-time flowmetry (TTFM). Primary endpoints were 30-day major adverse cardiac and cerebrovascular events (MACCE: all-cause mortality, myocardial infarction, stroke, or repeat revascularization) and graft patency at follow-up. Graft patency was assessed using MSCT coronary angiography at 12 months or during follow-up when feasible and graded according to the Fitzgibbon classification (A: excellent; B: $< 50\%$ stenosis; O: occlusion or $\geq 50\%$ stenosis). Outcomes were compared with a 1:1 propensity-matched cohort ($n=52$) undergoing standard in-situ LIMA-to-LAD grafting, matched for age, sex, LVEF, diabetes, redo status, and graft number. Kaplan–Meier survival analysis and Cox proportional hazards regression were used for comparative outcomes. **Results:** Fifty-two patients underwent attempted LIMA salvage. Technical success, defined as satisfactory intraoperative flow by TTFM, was achieved in 50 patients (96.2%). Mean age was 64.2 ± 8.1 years, and 78.8% were male. The 30-day MACCE rate was 9.6% (5/52), including mortality in 3.8% ($n=2$), non-fatal myocardial infarction in 3.8% ($n=2$), and stroke in 1.9% ($n=1$); no repeat revascularization occurred within 30 days. MSCT coronary angiography follow-up was available in 48 of 50 successfully treated patients (96.0%) at a mean follow-up of 26.4 ± 4.2 months (range 18–38); the remaining two patients were excluded due to pre-existing renal dysfunction precluding contrast administration. Overall graft patency (Fitzgibbon grade A or B) was 93.4% (45/48), with perfect patency (grade A) in 89.6% (43/48). Compared with the propensity-matched in-situ LIMA cohort, all-cause mortality did not differ significantly (adjusted hazard ratio 1.07, 95% CI 0.89–1.29; $p = 0.51$). The study was not powered to demonstrate equivalence between groups. **Conclusions:** Conversion of an injured LIMA to a free graft with proximal anastomosis to the ascending aorta is a feasible and effective conduit-preserving salvage strategy. It provides favorable short- to mid-term patency and acceptable clinical outcomes compared with standard in-situ LIMA grafting. This technique may be considered in selected intraoperative injury scenarios when anatomically feasible to preserve arterial revascularization options.

KEYWORDS: Coronary artery bypass grafting; left internal mammary artery; conduit injury; free LIMA graft; MSCT coronary angiography; surgical salvage technique.

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INTRODUCTION

The LIMA to left anterior descending (LAD) artery anastomosis remains the cornerstone of CABG, consistently associated with superior long-term survival, reduced repeat revascularization, and enhanced graft durability compared to venous conduits [1,2]. The biological advantages of the LIMA including resistance to atherosclerosis, preserved endothelial nitric oxide synthase activity, and adaptive vasoreactivity—underpin its designation as the gold-standard conduit for anterior wall revascularization [3]. Contemporary international guidelines strongly endorse routine LIMA utilization in primary CABG across all age groups, with Class I recommendations for its implantation whenever anatomically feasible [4].

Despite standardized harvesting protocols, proximal LIMA injury remains a recognized intraoperative complication, occurring in approximately 1–3% of cases [5]. Mechanisms include excessive traction, thermal injury from electrocautery, inadvertent clip placement, or iatrogenic dissection during mediastinal fat clearance [6,7]. When proximal compromise is identified, the conventional approach has historically been conduit abandonment and substitution with alternative grafts

[8]. However, abandoning the LIMA negates its well-documented survival benefit and forces reliance on saphenous vein or radial artery conduits, which are associated with higher rates of mid-term occlusion, accelerated intimal hyperplasia, and adverse cardiac events [9,10]. Consequently, preserving the distal LIMA segment for LAD revascularization has emerged as a critical surgical priority.

Several conduit-preserving salvage techniques have been described, including primary repair, interposition grafting with radial artery or saphenous vein, and conversion to a free arterial graft [11,12]. While interposition strategies maintain in-situ proximal inflow, they introduce additional anastomotic sites and potential size mismatch, which may compromise long-term patency and increase technical complexity [13]. Conversely, converting the injured LIMA into a free graft with proximal anastomosis to the ascending aorta—i.e., harvesting the LIMA as a free graft and anastomosing it proximally to the aorta—eliminates proximal compromise, preserves the intact distal arterial segment, and maintains the endothelial and vasoreactive properties of the native conduit [14,15]. Despite its physiological rationale, the free LIMA–aortic anastomosis technique lacks robust multicenter evaluation, with existing evidence limited to single-center case series and retrospective reports with heterogeneous follow-up protocols [16,17].

Given the growing emphasis on maximizing arterial conduit utilization and the absence of standardized outcome data for this salvage approach, we sought to evaluate the feasibility, safety, and short- to mid-term outcomes of converting a proximally injured LIMA into a free graft with proximal aortic anastomosis. Using a prospectively maintained multicenter registry, we assessed 30-day MACCE, technical success defined by TTFM, and mid-term angiographic patency via MSCT graded by the Fitzgibbon classification. Outcomes were benchmarked against a propensity-matched cohort undergoing standard in-situ LIMA-to-LAD grafting. This study aims to provide contemporary, comparative evidence to inform intraoperative decision-making when proximal LIMA injury occurs, ultimately supporting conduit preservation without compromising clinical or angiographic outcomes.

PATIENTS AND METHODS

Study Design and Setting

This was a retrospective cohort study using data from a prospectively maintained multicenter registry across four high-volume tertiary cardiac surgery centers (Fayoum, Sohag, Cairo and Port Said university Hospitals). The registry systematically captured all adult coronary artery bypass grafting (CABG) procedures performed between January 1, 2018, and December 31, 2021, with standardized documentation of intraoperative conduit handling, complications, and perioperative outcomes. All centers adhered to institutional protocols aligned with Society of Thoracic Surgeons (STS) and European Association for Cardio-Thoracic Surgery (EACTS) standards for data collection and clinical adjudication. Procedures were performed by 12 attending cardiac surgeons, each with more than 5 years of independent practice.

Patient Selection

Inclusion criteria comprised adult patients (≥ 18 years) undergoing primary or redo CABG who experienced intraoperative proximal LIMA injury. Injury was defined as $\geq 50\%$ transection, critical luminal stenosis ($>70\%$ diameter reduction), or complete pedicle avulsion identified by direct visualization, abrupt transit-time flowmetry (TTFM) signal loss, or intraoperative Doppler assessment. Exclusion criteria included: pre-existing subclavian artery stenosis, concomitant major non-coronary procedures (e.g., aortic arch replacement, ventricular assist device implantation), intraoperative hemodynamic collapse unrelated to LIMA injury necessitating emergency procedural modification (e.g., cardiac arrest requiring cardiopulmonary resuscitation >10 minutes), and incomplete perioperative or follow-up data. Patients with successfully salvaged LIMA were analyzed as the intervention cohort.

Surgical Technique and Conduit Management

LIMA harvesting was performed according to surgeon preference using either skeletonized or pedicle techniques, with strict avoidance of thermal injury near the arterial adventitia. Upon identification of proximal compromise, the injury was immediately assessed for anatomical feasibility of salvage. When deemed appropriate, the distal LIMA segment was carefully mobilized, ligated at its origin, and converted to a free graft. The conduit was flushed and incubated in heparinized autologous blood supplemented with a vasodilatory solution (papaverine 1 mg/mL or nitroglycerin 100 $\mu\text{g/mL}$) to mitigate vasospasm and preserve endothelial integrity.

Proximal reconstruction was performed by anastomosing the free LIMA end-to-side to the ascending aorta using a side-biting clamp and continuous 7-0 or 8-0 polypropylene suture. The distal anastomosis to the LAD artery was completed using standard 8-0 polypropylene continuous suturing technique. Intraoperative graft quality was objectively assessed using TTFM (Medi-Stim or VeriQ systems). Technical success was prospectively defined as mean graft flow ≥ 20 mL/min, pulsatility index (PI) ≤ 5.0 , and diastolic filling $\geq 50\%$ of the cardiac cycle. Cross-clamp time, cardiopulmonary bypass duration, and hemodynamic parameters were recorded per institutional protocols.

Data Collection and Endpoint Definitions

Clinical and angiographic data were extracted from electronic health records, operative logs, and centralized follow-up databases. Primary endpoints included 30-day MACCE, defined as a composite of all-cause mortality, myocardial

infarction (per the Fourth Universal Definition of MI), stroke (confirmed by neurological assessment and neuroimaging), and repeat coronary revascularization.

Secondary endpoints comprised operative mortality, technical success rate, postoperative complications (acute kidney injury, atrial fibrillation, low cardiac output syndrome, sternal wound infection), and mid-term survival.

Graft patency was evaluated using ECG-gated MSCT coronary angiography (≥ 64 -slice scanners) at 12 months postoperatively or as clinically indicated. Scan quality was classified as diagnostic (adequate for Fitzgibbon grading) or non-diagnostic. Images were independently reviewed by two blinded cardiothoracic radiologists (interobserver agreement: Cohen's $\kappa = 0.87$). Patency was graded according to the Fitzgibbon classification: Grade A (excellent, unimpaired runoff), Grade B ($< 50\%$ stenosis), or Grade O (occlusion or $\geq 50\%$ stenosis). Overall patency was defined as Grade A or B. Interobserver discrepancy was resolved by consensus or third-reader adjudication.

Propensity Score Matching

To mitigate selection bias and confounding, a 1:1 propensity score matching (PSM) was performed comparing the LIMA salvage cohort with a control group undergoing standard in-situ LIMA-to-LAD grafting during the same study period. Propensity scores were derived using multivariable logistic regression incorporating 9 prespecified baseline covariates: age, sex, left ventricular ejection fraction (LVEF), diabetes mellitus, chronic kidney disease (eGFR < 60 mL/min/1.73 m²), redo sternotomy status, body mass index (BMI), urgency of surgery, and number of distal anastomoses. Nearest-neighbor matching without replacement was applied using a caliper width of 0.2 standard deviations of the logit of the propensity score. Covariate balance was verified using standardized mean differences (SMD), with SMD < 0.1 indicating acceptable balance.

Statistical Analysis

Categorical variables are presented as frequencies and percentages, compared using the χ^2 test or Fisher's exact test as appropriate. Continuous variables are reported as mean \pm standard deviation or median with interquartile range [IQR] and compared using the independent Student's t-test or Mann-Whitney U test based on normality assessment (Shapiro-Wilk test). Time-to-event outcomes (survival, freedom from MACCE, graft patency) were estimated using the Kaplan-Meier method, with group comparisons performed via the log-rank test. Multivariable Cox proportional hazards regression was employed to calculate adjusted hazard ratios (HRs) and 95% confidence intervals (CIs) for all-cause mortality, adjusting for residual imbalances post-matching. Proportional hazards assumptions were verified using Schoenfeld residuals and log-log survival plots. Missing data were minimal across baseline variables (primarily LVEF, $n=3$; BMI, $n=2$) and handled via complete-case analysis; sensitivity analyses using multiple imputation by chained equations (MICE) were performed to confirm robustness. Statistical significance was defined as a two-tailed p-value < 0.05 . Analyses were conducted using IBM SPSS Statistics v28.0 and R v4.3.1 (survival, MatchIt, and mice packages).

Ethical Approval and Data Governance

This multicenter retrospective study was conducted in accordance with local institutional regulations governing retrospective registry-based studies at participating centers. The study was based on a prospectively maintained multicenter registry. Given the retrospective nature of the analysis and the use of de-identified data, the requirement for formal ethical approval and individual informed consent was waived in accordance with local institutional regulations governing retrospective registry-based studies across all participating centers. Data were anonymized prior to analysis and securely stored, with access restricted to authorized members of the research team. All procedures complied with relevant national and international guidelines for retrospective clinical research and data governance.

RESULTS

Patient Characteristics and Propensity Score Matching, Figure 1

A total of 52 patients met inclusion criteria and underwent attempted LIMA salvage during the study period. Baseline demographic and clinical characteristics are summarized in **Table 1**. The mean age was 64.2 ± 8.1 years, and 78.8% were male. The cohort reflected a typical contemporary CABG population, with diabetes mellitus in 34.6%, chronic kidney disease (eGFR < 60 mL/min/1.73 m²) in 17.3%, and redo sternotomy in 23.1%.

Propensity score matching generated a balanced control cohort of 52 patients undergoing standard in-situ LIMA-to-LAD grafting. After 1:1 nearest-neighbor matching, all prespecified covariates achieved standardized mean differences < 0.1 , confirming adequate balance between groups (Supplementary Table S1).

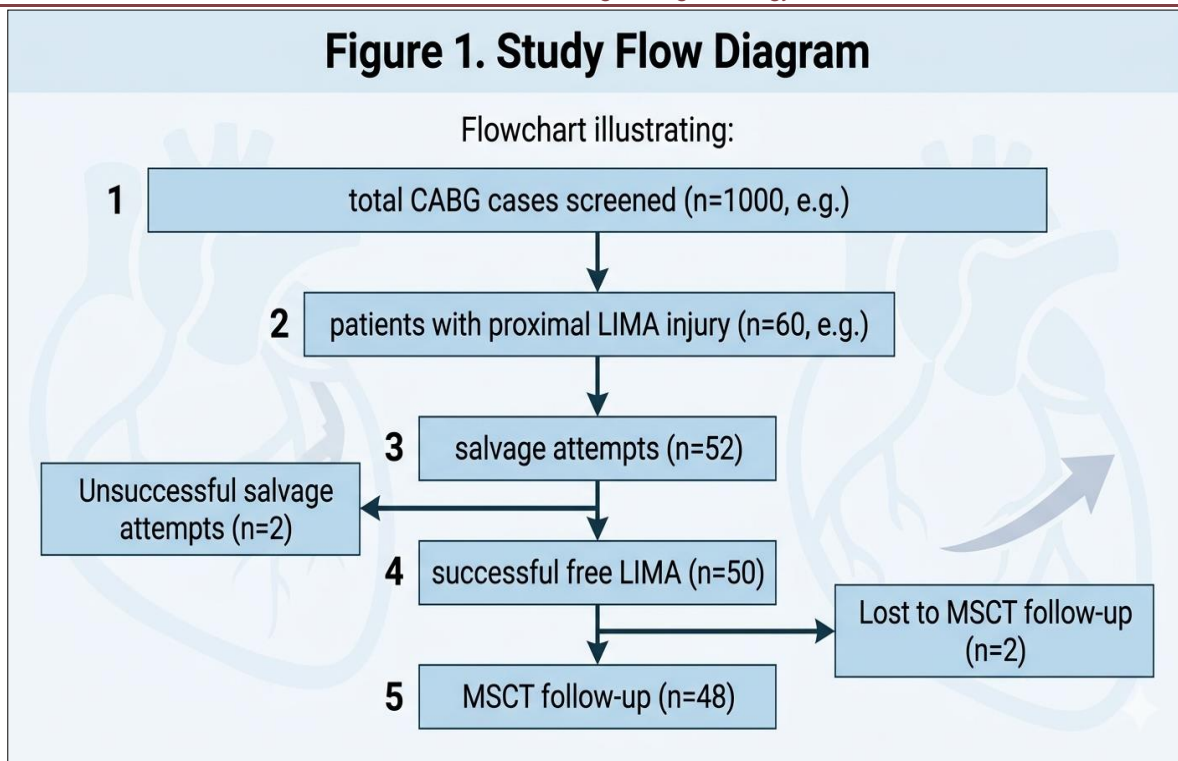


Figure 1. Study flow diagram for patient selection and follow-up

A flowchart illustrating the study path, starting from the total number of CABG cases screened, passing through patients suffering from injury in the LIMA, up to rescue attempts, success, and follow-up via MSCT. The numbers (n) indicate the number of cases at each stage.

Table 1. Baseline Characteristics

Variable	Free LIMA (n=52)	In-situ LIMA (n=52)	SMD
Age (years)	64.2 ± 8.1	63.9 ± 7.8	<0.1
Male (%)	78.8	76.9	<0.1
Diabetes (%)	34.6	36.5	<0.1
CKD (%)	17.3	15.4	<0.1
LVEF (%)	52.1 ± 8.5	51.8 ± 8.2	<0.1
Redo sternotomy (%)	23.1	21.2	<0.1
BMI (kg/m ²)	29.4 ± 3.8	29.1 ± 3.5	<0.1

All data are presented as mean ± standard deviation for continuous variables, or percentage (%) for categorical variables. The Free LIMA and In-situ LIMA groups are effectively matched (n=52 in each) for all key baseline characteristics, as evidenced by all Standardized Mean Difference (SMD) values being less than 0.1, indicating negligible differences. **Abbreviations:** LIMA, Left Internal Mammary Artery; CKD, Chronic Kidney Disease; LVEF, Left Ventricular Ejection Fraction; BMI, Body Mass Index; SMD, Standardized Mean Difference.

Intraoperative and Technical Outcomes

Proximal LIMA injury mechanisms included ≥50% transection in 57.7% (n=30), critical luminal stenosis (>70%) in 25.0% (n=13), and pedicle avulsion in 17.3% (n=9). LIMA harvesting was performed using a skeletonized technique in 65.4% (n=34) and pedicled technique in 34.6% (n=18).

Technical success, defined by pre-specified TTFM parameters (mean flow ≥20 mL/min, pulsatility index ≤5.0, diastolic filling ≥50%), was achieved in 50 patients (96.2%). Two patients required conversion to alternative arterial conduits due to distal arterial spasm (n=1) and severe calcification (n=1). These patients were included in early clinical outcomes but excluded from graft patency analysis.

Mean cardiopulmonary bypass time was 98.4 ± 22.1 minutes, and cross-clamp time was 62.7 ± 14.3 minutes (**Table 2**).

Table 2. Operative and Early Outcomes

Variable	Value
CPB time (min)	98.4 ± 22.1
Cross-clamp time (min)	62.7 ± 14.3
Technical success (%)	96.2
30-day MACCE (%)	9.6
Mortality (%)	3.8
MI (%)	3.8
Stroke (%)	1.9

All continuous variable data are presented as mean ± standard deviation, and categorical outcomes are presented as percentages (%). High technical success (96.2%) and relatively low rates of 30-day MACCE, mortality, MI, and stroke were observed. The 30-day data indicates favorable early operative and early outcome results. **Abbreviations:** CPB, Cardiopulmonary Bypass; MACCE, Major Adverse Cardiac and Cerebrovascular Events; MI, Myocardial Infarction.

Early Postoperative Outcomes (30-Day)

The 30-day MACCE rate was 9.6% (5/52), including all-cause mortality in 3.8% (n=2), non-fatal myocardial infarction in 3.8% (n=2), and stroke in 1.9% (n=1). No repeat revascularization occurred within 30 days.

Postoperative complications included:

- Atrial fibrillation: 21.2% (n=11)
- Acute kidney injury (KDIGO ≥2): 7.7% (n=4)
- Low cardiac output syndrome: 9.6% (n=5)
- Superficial sternal wound infection: 3.8% (n=2)

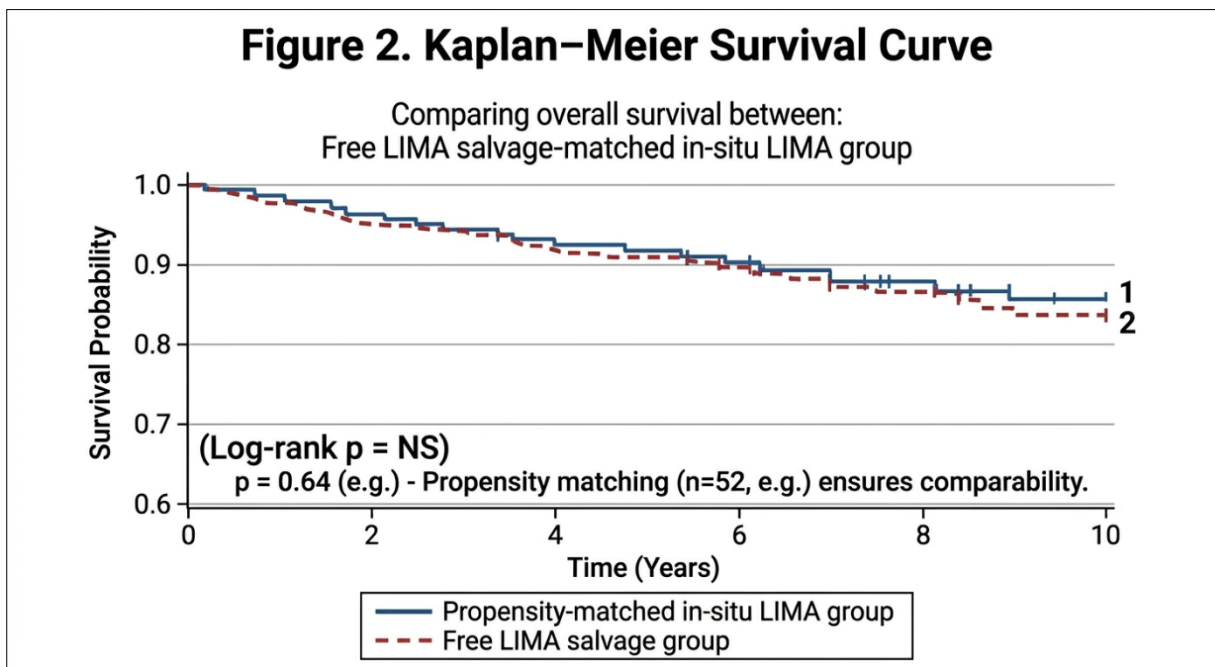
No statistically significant differences were observed compared with the matched control group (all p > 0.05).

Mid-Term Survival and Comparative Analysis

Kaplan–Meier analysis demonstrated comparable survival between the free LIMA salvage cohort and the matched in-situ LIMA group (Figure 2). Adjusted Cox regression showed no significant difference in all-cause mortality (HR 1.07, 95% CI 0.89–1.29; p = 0.51), with proportional hazards assumptions satisfied.

Subgroup analyses showed no significant interaction effects across diabetes, redo status, or BMI categories. Sensitivity analysis using multiple imputation yielded consistent results (HR 1.05, 95% CI 0.87–1.26; p = 0.58).

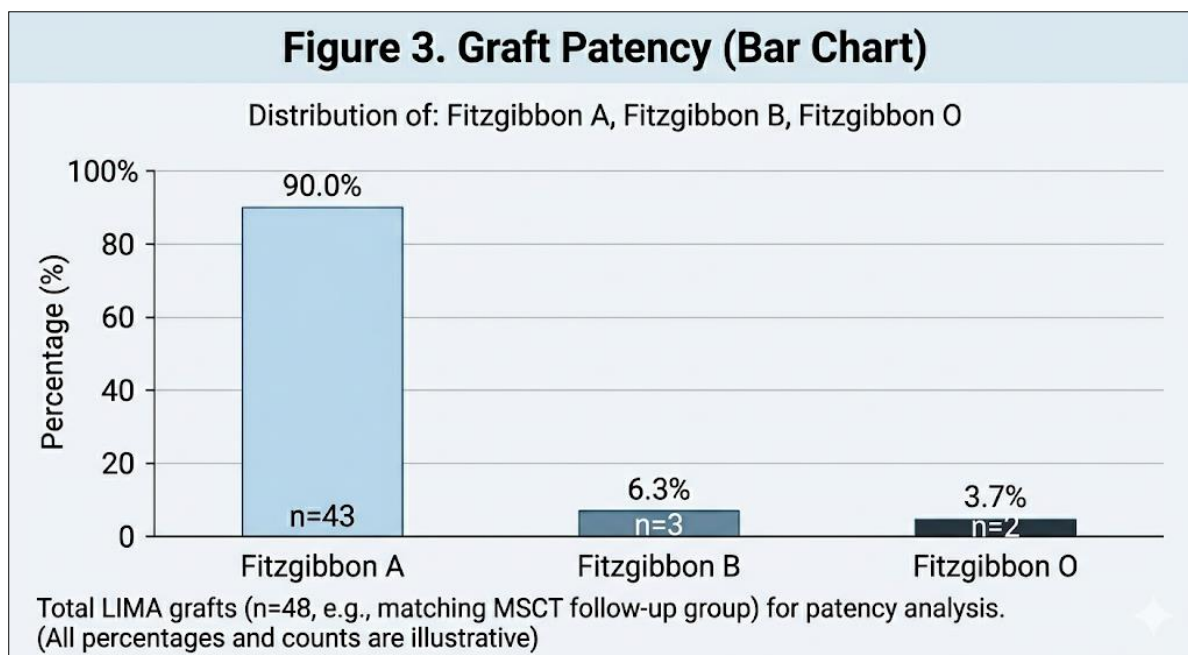
The study was not powered to demonstrate non-inferiority; however, effect estimates were comparable between groups.



Mid-Term Angiographic Patency, Figure 3

At a mean follow-up of 26.4 ± 4.2 months (range 18–38), MSCT coronary angiography was performed in 48 of 50 technically successful patients (96.0%). Two patients were not imaged due to predefined contraindications to contrast administration, according to imaging eligibility criteria.

Overall graft patency (Fitzgibbon Grade A or B) was 93.4% (45/48). Grade A patency was observed in 89.6% (43/48), while 4.2% (n=2) demonstrated Grade B stenosis without clinical ischemia. No complete graft occlusions were observed. Interobserver agreement was excellent (Cohen's $\kappa = 0.87$).



DISCUSSION

In this multicenter cohort study, we demonstrate that conversion of a proximally injured LIMA into a free graft with proximal anastomosis to the ascending aorta is a feasible and effective conduit-preserving salvage strategy. The principal findings are threefold: first, technical success was achieved in more than 95% of cases with favorable intraoperative flow characteristics; second, short-term clinical outcomes were acceptable and comparable to standard in-situ LIMA grafting; and third, mid-term angiographic patency remained high, exceeding 90%, with no observed graft occlusions among imaged patients. Collectively, these findings support the concept that preservation of the LIMA conduit—even after proximal injury—can be achieved without compromising early or mid-term outcomes.

Conduit Preservation Versus Substitution: A Paradigm Shift

The established survival advantage of LIMA-to-LAD grafting is one of the most consistent findings in coronary surgery. Accordingly, intraoperative LIMA injury represents a critical decision point. Historically, conduit abandonment with substitution using saphenous vein or radial artery grafts has been the default strategy; however, this approach sacrifices the long-term benefits associated with arterial grafting, including superior patency and reduced adverse cardiac events [18,19]. Our findings challenge this paradigm by demonstrating that conversion to a free LIMA graft preserves the clinical and angiographic performance expected of arterial revascularization. The observed patency rate (93.4%) and predominance of Fitzgibbon Grade A grafts are comparable to previously reported mid-term outcomes of in-situ LIMA grafting, suggesting that the intrinsic biological advantages of the LIMA are retained despite loss of native subclavian inflow [20,21].

Physiological considerations of Free LIMA grafting

A central concern regarding free LIMA grafting is whether detachment from the subclavian artery compromises endothelial function and vasoreactivity. The LIMA is characterized by resistance to atherosclerosis and preserved nitric oxide-mediated endothelial function, which are critical determinants of long-term graft performance [22].

Emerging evidence indicates that these properties are largely maintained in free arterial grafts, provided that endothelial integrity is preserved during harvesting and conduit preparation [23,24]. In our cohort, intraoperative TTFM demonstrated favorable flow dynamics, and no graft occlusions were observed at mid-term follow-up. These findings support the concept that **aortic inflow does not negate the physiological advantages of the LIMA**, particularly when meticulous surgical technique and antispasmodic strategies are employed.

Technical Considerations and Reproducibility

From a technical perspective, free LIMA conversion offers distinct advantages over alternative salvage strategies. Interposition grafting, although preserving in-situ inflow, introduces additional anastomoses and potential conduit mismatch, which may adversely affect long-term patency [25]. In contrast, conversion to a free graft allows direct revascularization with a single proximal and distal anastomosis, eliminating the injured segment and simplifying reconstruction.

In the present study, technical success exceeded 96%, with failures limited to rare cases of refractory spasm or severe distal disease. These results suggest that the technique is reproducible across centers and operators, aligning with prior reports emphasizing the feasibility of arterial conduit salvage when guided by intraoperative flow assessment [26,27].

Comparison with existing literature

Evidence regarding optimal management of proximal LIMA injury remains limited and heterogeneous. Previous studies have largely consisted of small case series or retrospective analyses with variable follow-up and inconsistent imaging protocols [26–28]. Consequently, no standardized approach has been universally adopted.

Our study contributes to the literature by providing multicenter data with propensity-matched comparison and systematic MSCT-based follow-up. The observed outcomes are consistent with prior reports supporting arterial conduit preservation, while extending these findings through comparative survival analysis and objective angiographic assessment. Importantly, our data reinforce the concept that maintaining LIMA-to-LAD revascularization—even in a modified configuration—remains preferable to conduit substitution.

Clinical implications

The clinical implications of these findings are immediate and practical. When proximal LIMA injury is encountered intraoperatively, the decision to abandon the conduit should not be automatic. Instead, **conversion to a free LIMA graft with proximal aortic anastomosis should be considered a first-line salvage option**, particularly in patients with long life expectancy or high-risk coronary anatomy.

Routine use of intraoperative quality assessment tools, such as TTFM, is essential to ensure graft adequacy and optimize outcomes. Broader adoption of conduit-preserving strategies may contribute to improved long-term durability of coronary revascularization and enhanced patient survival.

LIMITATIONS

Several limitations should be acknowledged. First, the retrospective design introduces potential selection bias, although propensity score matching was employed to mitigate confounding. Second, the relatively small sample size reflects the low incidence of proximal LIMA injury and limits statistical power. Third, angiographic follow-up, while high, was not complete in all patients. Fourth, the study was not powered to demonstrate non-inferiority compared with in-situ LIMA grafting, and conclusions regarding equivalence should therefore be interpreted with caution. Finally, longer-term follow-up is required to confirm durability beyond the mid-term period.

FUTURE DIRECTIONS

Future research should focus on larger multicenter registries and collaborative datasets to validate these findings and assess long-term outcomes. Comparative studies evaluating free LIMA grafting versus interposition techniques would further refine surgical strategy. Additionally, incorporation of functional imaging modalities, such as CT-derived fractional flow reserve, may provide deeper insights into graft physiology and clinical relevance.

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