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Article

In-Hospital Outcomes of Revascularization in Patients with Left Ventricular Systolic Dysfunction and Coronary Chronic Total Occlusion

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Abstract

Background: The in-hospital outcomes of percutaneous coronary intervention (PCI) or coronary artery bypass grafting (CABG) in patients with left ventricular systolic dysfunction (LVSD) and chronic total occlusion (CTO) remain unclear. **Methods**: From 2014 to 2020, patients with LVSD and CTO who underwent PCI or CABG were collected. The primary endpoint was in-hospital major adverse cardiac or cerebrovascular events (MACCE), defined as the composite of all-cause mortality, cardiovascular mortality, stroke, myocardial infarction (MI), and target vessel revascularization. Inverse probability of treatment weighting (IPTW) was performed to evaluate the association between revascularization strategies and in-hospital outcomes. The hazard ratio (HR) and 95% confidence interval (CI) were calculated using the Cox proportional hazards model. **Results**: Of the 773 patients who met the inclusion criteria, 543 (70.2%) underwent PCI, and 230 (29.8%) underwent CABG. The primary endpoint was observed in 25 (3.2%) patients. The incidence of in-hospital MACCE (6.5% *vs.* 1.8%, $p < 0.001$) was significantly higher in the CABG group than in the PCI group. After IPTW, the risk of in-hospital MACCE was not found to be significantly different between CABG and PCI groups (HR = 1.81; 95% CI: 0.37–8.82; $p = 0.460$). Compared with patients who underwent PCI, those who underwent CABG exhibited a significantly higher risk of MI (HR = 6.92; 95% CI: 1.24–38.60; $p = 0.027$). **Conclusions**: Patients with LVSD and CTO could experience better outcomes with PCI, which offers a safer alternative coronary revascularization strategy and a reduced risk of MI.

Keywords:

percutaneous coronary intervention; coronary artery bypass grafting; left ventricular systolic dysfunction; chronic total occlusion

Introduction

Left ventricular function is an important consideration when selecting a coronary revascularization strategy. Coronary heart disease is the most prevalent cause of left ventricular systolic dysfunction (LVSD) and is associated with a poor prognosis [1,2]. The number of patients undergoing coronary angiography due to LVSD has shown an increasing trend. Therefore, more patients were diagnosed with coronary heart disease. Nearly half of the patients were referred for revascularization via percutaneous coronary intervention (PCI) or coronary artery bypass grafting (CABG) [3]. Current guidelines indicate that CABG is usually preferred for planned revascularization in patients with LVSD [4–6]. Nevertheless, the proportion of patients undergoing PCI increases in clinical practice due to individual differences in diseases, the decision-making of medical teams, and patient preferences [3,7,8]. The presence of chronic total occlusion (CTO) is observed in approximately half of the patients with LVSD and is accompanied by more adverse comorbidities. These patients constitute the most complex population, characterized by intricate coronary artery lesions, poor cardiac function, and burdensome comorbidities, all of which collectively represent a significant risk for revascularization [7,9,10]. The combined effect of these adverse factors may increase the risk of mortality, as these patients have poor tolerance to ischemia and the potential for fatal perioperative complications [11,12]. Data from the Nationwide Inpatient Sample database indicates that such patients have a significantly higher risk of in-hospital complications following PCI, resulting in substantial financial consequences [13]. Consequently, it is necessary to evaluate the risk of complications in this high-risk group and limit the incidence of in-hospital adverse events.

No guidelines have been published on revascularization in patients with LVSD and CTO, and evidence-based medical data on the postprocedural outcomes in such patients is inadequate. The purpose of evaluating the in-hospital outcomes of revascularization in patients with LVSD and CTO was to facilitate procedure risk assessment and provide insights into heart team discussions and medi-

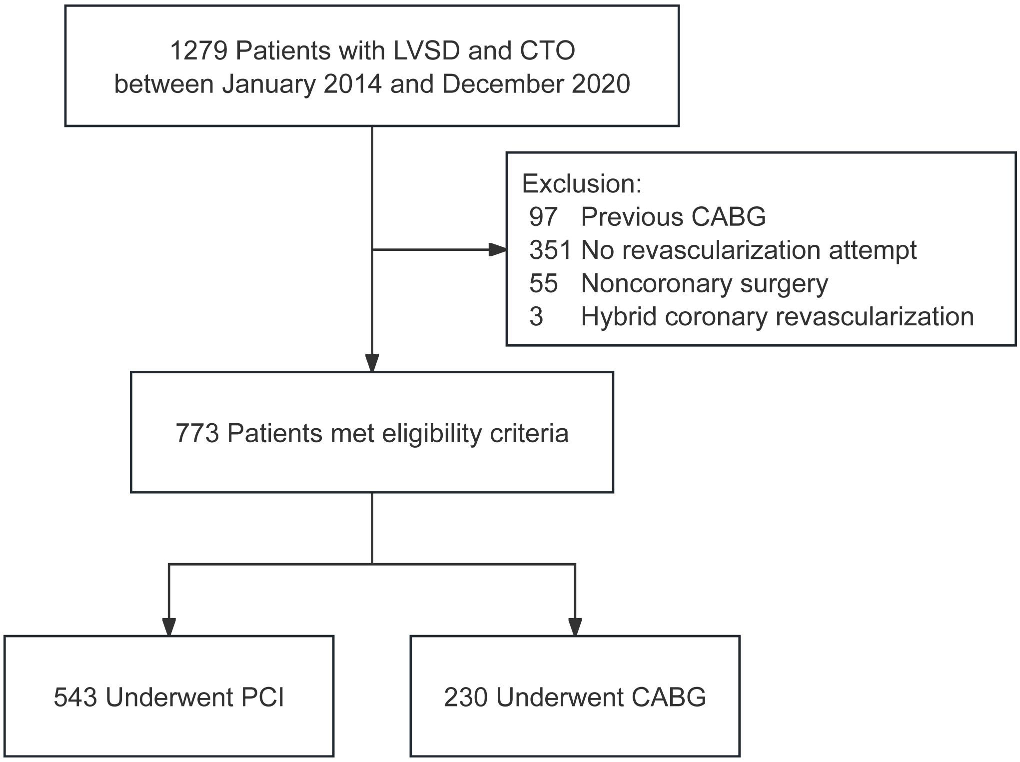

Fig. 1. Flow chart of the study. Abbreviations: CABG, coronary artery bypass grafting; CTO, chronic total occlusion; LVSD, left ventricular systolic dysfunction; PCI, percutaneous coronary intervention.

cal decisions. This study compared the effects of PCI and CABG on in-hospital outcomes in patients with LVSD and CTO using real-world data from high-volume heart centers. It is anticipated that the findings of this study will provide valuable insights into patient consultation, patient selection, risk/benefit assessment, and patient referral.

Methods

Study Design

From January 2014 to December 2020, data were collected in this retrospective observational cohort study of patients with LVSD who underwent coronary angiography to identify coronary artery CTO at the Beijing Anzhen Hospital, Capital Medical University. The exclusion criteria were as follows: (1) patients with previous CABG; (2) those who did not receive revascularization during hospitalization; (3) those who underwent hybrid coronary revascularization during hospitalization; (4) those who underwent noncoronary surgery during the same hospitalization. Due to the retrospective design of this study, the requirement for written informed consent was exempted. The study protocol was conducted following the principles of the Declaration of Helsinki. The Ethics Committee of the Beijing Anzhen Hospital, Capital Medical University approved this study protocol (No. 2023026X).

Data Collection

The medical record system collected the baseline clinical characteristics, laboratory examinations, echocardiographic parameters, angiographic characteristics, procedural characteristics, and in-hospital outcomes. The left ventricular ejection fraction (LVEF) was calculated from echocardiography using the modified biplane Simpson method. The echocardiographic parameters were recorded as the most recent preoperative measurements in our hospital.

Definitions and Endpoints

A preoperative LVEF $\leq$40% was defined as LVSD [4,14]. The CTO refers to the definition by the CTO Academic Research Consortium, which describes it as coronary obstruction with a Thrombolysis In Myocardial Infarction (TIMI) flow grade 0 and presumed or documented duration of $\geq$3 months [15]. The primary endpoint of this study was in-hospital major adverse cardiac or cerebrovascular events (MACCE), defined as the composite of all-cause mortality, cardiovascular mortality, stroke, myocardial infarction (MI), and target vessel revascularization [16]. The secondary endpoints were the individual components of the primary endpoint, as defined by the Academic Research Consortium-2 [16].

Table 1. Demographic and clinical characteristics.

	Overall	PCI	CABG	p
	(N = 773)	(n = 543)	(n = 230)	
Male	673 (87.1)	467 (86.0)	206 (89.6)	0.177
Age, years	58.80 ± 10.16	58.51 ± 10.48	59.47 ± 9.36	0.210
BMI, kg/m^2	25.81 ± 3.38	25.96 ± 3.53	25.44 ± 2.99	0.036
BMI class				0.744
Underweight BMI	9 (1.2)	6 (1.1)	3 (1.3)	
Healthy BMI	326 (42.2)	225 (41.4)	101 (43.9)	
Overweight BMI	438 (56.7)	312 (57.5)	126 (54.8)	
Smoker	476 (61.6)	330 (60.8)	146 (63.5)	0.480
Current smoker	273 (35.3)	185 (34.1)	88 (38.3)	0.265
Hypertension	455 (58.9)	329 (60.6)	126 (54.8)	0.134
Diabetes mellitus	398 (51.5)	271 (49.9)	127 (55.2)	0.177
Diabetes mellitus with insulin	153 (19.8)	104 (19.2)	49 (21.3)	0.492
Dyslipidemia	542 (70.1)	395 (72.7)	147 (63.9)	0.014
CKD	61 (7.9)	46 (8.5)	15 (6.5)	0.358
Previous cerebral infarction	109 (14.1)	73 (13.4)	36 (15.7)	0.420
Previous MI	495 (64.0)	356 (65.6)	139 (60.4)	0.174
Previous PCI	264 (34.2)	211 (38.9)	53 (23.0)	<0.001
Previous VT/VF	43 (5.6)	37 (6.8)	6 (2.6)	0.020
COPD	21 (2.7)	12 (2.2)	9 (3.9)	0.183
Peripheral vascular disease	48 (6.2)	31 (5.7)	17 (7.4)	0.376
NYHA class ≥3	260 (33.6)	152 (28.0)	108 (47.0)	<0.001
STEMI	73 (9.4)	61 (11.2)	12 (5.2)	0.009
Triacylglycerol, mmol/L	1.50 (1.09, 2.11)	1.55 (1.13, 2.18)	1.42 (1.06, 1.92)	0.016
Total cholesterol, mmol/L	3.87 (3.29, 4.68)	3.92 (3.33, 4.70)	3.82 (3.23, 4.65)	0.198
HDL-C, mmol/L	0.94 (0.82, 1.10)	0.95 (0.82, 1.10)	0.93 (0.82, 1.10)	0.327
LDL-C, mmol/L	2.29 (1.80, 2.90)	2.29 (1.81, 2.90)	2.28 (1.79, 2.88)	0.651
Creatinine clearance rate, mL/min	88.63 (67.16, 111.39)	89.22 (66.35, 112.66)	88.13 (68.12, 107.92)	0.620
LVEF, %	35.58 ± 4.97	35.27 ± 5.28	36.32 ± 4.07	0.003
LVEDD, mm	59.44 ± 7.11	59.73 ± 7.46	58.76 ± 6.17	0.062
LVESD, mm	46.93 ± 8.15	47.28 ± 8.59	46.12 ± 6.95	0.049
Functional examination	89 (11.5)	56 (10.3)	33 (14.3)	0.108

Data are presented as mean ± standard deviation, median (Q1, Q3) or counts (%). Abbreviations: BMI, body mass index; CABG, coronary artery bypass grafting; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; HDL, high-density lipoprotein; LDL, low-density lipoprotein; LVEDD, left ventricular end-diastolic dimension; LVEF, left ventricular ejection fraction; LVESD, left ventricular end-systolic dimension; MI, myocardial infarction; NYHA, New York Heart Association; PCI, percutaneous coronary intervention; STEMI, ST-segment elevation myocardial infarction; VF, ventricular fibrillation; VT, ventricular tachycardia.

Statistical Analysis

Continuous variables are expressed as mean ± standard deviation or median with first quartile and third quartile. The Welch Two Sample t-test was used for normally distributed data to compare groups, whereas the Wilcoxon rank-sum test was used for non-normally distributed data. Categorical variables are presented as counts (percentages), and the groups were compared using the chi-square test or Fisher's exact test. The propensity score (PS)-based on inverse probability of treatment weighting (IPTW) was used to evaluate the effects of different revascularization strategies on the occurrence of in-hospital MACCE and its components. The PS was calculated using a multivariable logistic regression model with the revascularization strategy as the dependent variable, whereas general demographic characteristics and other preoperative variables were the independent variables. The IPTW assigned weights of PS and 1-PS to patients undergoing CABG and PCI, respectively. Differences between groups were compared using the standardized mean difference (SMD), with an SMD ≤0.20, indicating an acceptable balance. The hazard ratio (HR) and 95% confidence interval (CI) were calculated using the Cox proportional hazards model after IPTW. The revascularization strategy was the independent variable in the Cox model, whereas in-hospital MACCE and its components were the dependent variables. A p value < 0.05 on the

Table 2. Angiographic characteristics.

	Overall (N = 773)	PCI (n = 543)	CABG (n = 230)	*p*
Multivessel disease	670 (86.7)	448 (82.5)	222 (96.5)	<0.001
Double-vessel disease	223 (28.8)	174 (32.0)	49 (21.3)	0.003
Triple-vessel disease	448 (58.0)	275 (50.6)	173 (75.2)	<0.001
LM disease	95 (12.3)	48 (8.8)	47 (20.4)	<0.001
ULMCAD	41 (5.3)	19 (3.5)	22 (9.6)	<0.001
SYNTAX score	26.76 ± 9.32	24.96 ± 9.01	31.01 ± 8.65	<0.001
SYNTAX score ≥33	191 (24.7)	104 (19.2)	87 (37.8)	<0.001
Recommendation for CABG based on SYNTAX score II	598 (77.4)	420 (77.3)	178 (77.4)	0.990
EuroSCORE II	1.48 (0.97, 2.57)	1.35 (0.92, 2.24)	1.85 (1.08, 3.60)	<0.001
CTO lesion characteristics				
RCA CTO	415 (53.7)	271 (49.9)	144 (62.6)	0.001
LAD CTO	355 (45.9)	239 (44.0)	116 (50.4)	0.102
LCX CTO	256 (33.1)	182 (33.5)	74 (32.2)	0.717
LM CTO	5 (0.6)	3 (0.6)	2 (0.9)	0.637
In-stent CTO	96 (12.4)	72 (13.3)	24 (10.4)	0.276
Rentrop collateral grade ≥2	511 (66.1)	351 (64.6)	160 (69.6)	0.186
CTO SYNTAX score	0.69 (0.46, 0.88)	0.71 (0.50, 0.91)	0.60 (0.40, 0.82)	<0.001
Blunt stump	485 (62.7)	337 (62.1)	148 (64.3)	0.548
Calcification	323 (41.8)	242 (44.6)	81 (35.2)	0.016
Bending >45°	246 (31.8)	161 (29.7)	85 (37.0)	0.046
Occlusion length ≥20 mm	527 (68.2)	369 (68.0)	158 (68.7)	0.840
Reattempt	95 (12.3)	61 (11.2)	34 (14.8)	0.169
Proximal cap ambiguity	179 (23.2)	124 (22.8)	55 (23.9)	0.746
Absence of interventional collaterals	266 (34.4)	189 (34.8)	77 (33.5)	0.722
Moderate or severe tortuosity	101 (13.1)	66 (12.2)	35 (15.2)	0.248
J-CTO score	2 (1, 3)	2 (1, 3)	2 (1, 3)	0.852
PROGRESS CTO score	1 (0, 1)	1 (0, 1)	1 (0, 1)	0.682

Data are presented as mean ± standard deviation, median (Q1, Q3) or counts (%). Abbreviations: CABG, coronary artery bypass grafting; CTO, chronic total occlusion; EuroSCORE II, European System for Cardiac Operative Risk Evaluation II; J-CTO, Multicenter CTO Registry of Japan; LAD, left anterior descending artery; LCX, left circumflex artery; LM, left main; PCI, percutaneous coronary intervention; PROGRESS CTO, Prospective Global Registry for the Study of Chronic Total Occlusion Intervention; RCA, right coronary artery; SYNTAX, SYNergy between percutaneous coronary intervention with TAXus and cardiac surgery; ULMCAD, unprotected left main coronary artery disease.

two-sided test was considered statistically significant. All statistical analyses were performed using the R statistical package (version 4.2.2; R Project for Statistical Computing, Vienna, Austria).

Results

The study population comprised 773 patients with LVSD and CTO who met the inclusion criteria. The flow chart of the study is presented in Fig. 1. A total of 673 males were included in this study, with a mean age of 58.80 ± 10.16 years. Among them, 543 (70.2%) were treated with PCI, while 230 (29.8%) underwent CABG. Compared to the CABG group, the PCI group exhibited a higher body mass index, higher prevalence of dyslipidemia, previous PCI, and previous ventricular tachycardia/ventricular fibrillation, accompanied by a higher ST-segment elevation myocardial infarction ratio, higher triglyceride levels, and lower LVEF. However, the CABG group exhibited a worse New York Heart Association class. The baseline demographic and clinical characteristics are presented in Table 1.

Angiographic characteristics are summarized in Table 2. Compared to patients who underwent PCI, 96.5% of those who underwent CABG had multivessel disease, especially triple-vessel disease (75.2%). A higher proportion of patients in the CABG group were diagnosed with left main disease and unprotected left main coronary artery disease, and lesion complexity was higher, as indicated by a higher SYNergy between percutaneous coronary intervention with TAXus and cardiac surgery (SYNTAX) score, a higher proportion of SYNTAX score ≥33, and a higher European System for Cardiac Operative Risk Evaluation II (EuroSCORE II). Regarding the characteristics of CTO lesions, the PCI group revealed less frequent right coronary artery CTO but more calcification and higher CTO SYNTAX scores. No significant differences were observed between the two groups regarding the Multicenter CTO Registry of Japan (J-CTO) score and the Prospective Global Registry for the Study of Chronic Total Occlusion Intervention (PROGRESS CTO) score, which reflects CTO complexity.

The procedural characteristics of PCI and CABG are reported in Table 3. Radial access was the primary approach for percutaneous intervention. Stents were implanted in 389 patients (71.6%), with a median of 2 (1, 3) stents planted per patient. The mechanical circulatory support was used in 12 patients (2.2%), and more than half were required for emergency use. A total of 440 patients (81.0%) underwent CTO-PCI, and 281 (63.9%) achieved technical success. In the PCI group, 196 patients (36.1%) underwent reasonable incomplete revascularization. In the CABG group, a median of 3 (3, 4) grafts per patient was placed, of which 144 patients (62.6%) underwent internal mammary artery transplantation. A total of 195 patients (84.8%) underwent off-pump CABG, the primary type of circulatory support. Overall, 218 patients (94.8%) underwent CTO-CABG. Among all CABG patients, complete revascularization was achieved in 175 patients (76.1%).

A total of 25 patients (3.2%) experienced the primary endpoint, which was mainly driven by all-cause mortality. In-hospital MACCE was significantly higher in the CABG group than in the PCI group (6.5% *vs.* 1.8%, $p < 0.001$). Regarding the secondary endpoints, all-cause mortality, cardiovascular mortality, and MI were significantly lower in patients treated with PCI than in those treated with CABG. No significant differences in stroke or target vessel revascularization rates were observed between groups. Among other in-hospital outcomes, patients in the CABG group had a higher incidence of malignant ventricular arrhythmia, cardiac tamponade, acute renal failure, and cardiac shock (all $p < 0.05$). Postprocedural hospital stay for the CABG group was significantly longer than in the PCI group. The detailed characteristics of the in-hospital outcomes are listed in Table 4.

The SMD of all included variables was less than 0.20 in the IPTW model, indicating a reasonable balance between the two groups (**Supplementary Fig. 1**). Table 5 presents the hazard ratios for the primary and secondary outcomes adjusted by IPTW. The primary endpoint, the risk of in-hospital MACCE, did not differ significantly between the two groups (HR = 1.81; 95% CI: 0.37–8.82; $p = 0.460$). Regarding secondary endpoints, a significant correlation was observed between CABG and a higher risk of MI (HR = 6.92; 95% CI: 1.24–38.60; $p = 0.027$). Other secondary endpoints did not differ significantly between the two groups after IPTW adjustment.

Table 3. Procedural characteristics.

PCI	n = 543
Radial access	479 (88.2)
Femoral access	136 (25.0)
IVUS/OCT	32 (5.9)
Balloon angioplasty	18 (3.3)
Drug-coated balloon	23 (4.2)
Stent	389 (71.6)
Total number of stents	2 (1, 3)
Use of MCS	12 (2.2)
Urgent MCS	7 (1.3)
CTO-PCI attempt	440 (81.0)
Residual SYNTAX score ≤8	196 (36.1)
CABG	**n = 230**
Total number of grafts	3 (3, 4)
Use of internal mammary artery	144 (62.6)
Type of cardiocirculatory support	
Off-pump CABG	195 (84.8)
On-pump beating heart CABG	24 (10.4)
On-pump CABG	11 (4.8)
Duration of ventilator use, hour	36.25 (21.00, 68.00)
Blood transfusion, mL	0 (0, 400)
CTO-CABG	218 (94.8)
Complete revascularization	175 (76.1)

Data are presented as median (Q1, Q3) or counts (%). Abbreviations: CABG, coronary artery bypass grafting; CTO, chronic total occlusion; IVUS, intravascular ultrasound; MCS, mechanical circulatory support; OCT, optical coherence tomography; PCI, percutaneous coronary intervention; SYNTAX, SYNergy between percutaneous coronary intervention with TAXus and cardiac surgery.

Discussion

This study examined 773 patients with LVSD and CTO who underwent PCI or CABG. We compared the differences in in-hospital outcomes between the two groups and determined the risk factors for in-hospital outcomes. The main findings of this study are summarized as follows. First, patients with LVSD and CTO had a high incidence of in-hospital MACCE after revascularization, which was primarily attributed to all-cause mortality. Second, CABG was significantly associated with an increased incidence of in-hospital MACCE compared with PCI. CABG remained an independent risk factor for MI after the IPTW adjustment.

With the aging population, an increase in life expectancy, and the rise in metabolic diseases, coronary heart disease with LVSD has emerged as a significant social burden that demands attention [17]. CTO, one of the most com-

Table 4. In-hospital outcomes.

	Overall (N = 773)	PCI (n = 543)	CABG (n = 230)	*p*
In-hospital MACCE	25 (3.2)	10 (1.8)	15 (6.5)	<0.001
All-cause mortality	18 (2.3)	8 (1.5)	10 (4.3)	0.015
Cardiovascular mortality	17 (2.2)	7 (1.3)	10 (4.3)	0.008
Stroke	10 (1.3)	4 (0.7)	6 (2.6)	0.073
MI	11 (1.4)	4 (0.7)	7 (3.0)	0.020
Target vessel revascularization	4 (0.5)	2 (0.4)	2 (0.9)	0.587
Malignant ventricular arrhythmia	34 (4.4)	12 (2.2)	22 (9.6)	<0.001
Cardiac tamponade	11 (1.4)	1 (0.2)	10 (4.3)	<0.001
Acute renal failure	14 (1.8)	5 (0.9)	9 (3.9)	0.007
Cardiac shock	37 (4.8)	13 (2.4)	24 (10.4)	<0.001
Multiorgan failure	6 (0.8)	3 (0.6)	3 (1.3)	0.370
Approach complications	4 (0.5)	1 (0.2)	3 (1.3)	0.081
Postprocedural hospital stay, day	3 (1, 7)	2 (1, 3)	8 (6, 11)	<0.001

Data are presented as median (Q1, Q3) or counts (%). Abbreviations: CABG, coronary artery bypass grafting; MACCE, major adverse cardiac or cerebrovascular events; MI, myocardial infarction; PCI, percutaneous coronary intervention.

Table 5. IPTW-adjusted hazard ratios for in-hospital outcomes.

	HR (95% CI)	*p*	*β*	*Standard error*
In-hospital MACCE	1.81 (0.37–8.82)	0.460	0.596	0.807
All-cause mortality	0.72 (0.21–2.44)	0.598	–0.329	0.623
Cardiovascular mortality	0.74 (0.21–2.60)	0.643	–0.296	0.638
Stroke	0.42 (0.07–2.51)	0.342	–0.865	0.911
MI	6.92 (1.24–38.60)	0.027	1.935	0.877
Target vessel revascularization	0.56 (0.07–4.37)	0.578	–0.584	1.050

The reference category is PCI. Abbreviations: CI, confidence interval; HR, hazard ratio; IPTW, inverse probability of treatment weighting; MACCE, major adverse cardiac or cerebrovascular events; MI, myocardial infarction.

plex coronary lesions, represents the end-stage of coronary artery stenosis. Unfortunately, it can be detected in half of patients with LVSD [10]. Patients diagnosed with LVSD and CTO had a higher number of burdensome comorbidities, including hypertension, diabetes, dyslipidemia, renal dysfunction, arrhythmias, and previous MI, which is consistent with previous studies [12,13,18]. These patients also had more complex coronary lesions [7]. Such features were corroborated by our study, in which 86.7% of the patients had multivessel disease, and 58.0% had a triple-vessel disease, with a mean SYNTAX score of 26.76 $\pm$ 9.32, while 24.7% of the patients in our study cohort had a SYNTAX score $\geq$33.

Patients with LVSD are prone to malignant arrhythmias, which are exacerbated by the presence of CTO. The Ventricular Arrhythmias and Chronic Total Coronary Occlusion (VACTO) primary study observed that CTO was independently associated with ventricular arrhythmia and death in patients receiving implantable cardioverter-defibrillators for the primary prevention of sudden cardiac death [19]. The VACTO Secondary Study, which evaluated outcomes in patients with an implantable cardioverter-defibrillator implanted for secondary prevention of sudden cardiac death, demonstrated that 50.6% of patients had at least one CTO and that such patients had higher rates of appropriate implantable cardioverter-defibrillator therapy and death during a median follow-up of 4.1 years. In the multivariate analysis, lower LVEF and CTO were independent risk factors for appropriate implantable cardioverter-defibrillator therapy and death [20]. The heterogeneity in repolarization caused by hibernating myocardium and scar tissue means that even in the presence of collateral circulation, the myocardial territory supplied by CTOs remains a substrate for inducing arrhythmias [21,22]. CTO can cause persistent regional myocardial ischemia, leading to local electrical instability around the marginal area of the myocardial scar, especially when heart pump function is impaired, further increasing the risk of malignant ventricular arrhythmia [23].

Second, there is an increased risk of MI in patients with LVSD and CTO. Due to the low fractional flow reserve of collateral vessels, the myocardium in the territory supplied by CTO vessels remains in a state of relative ischemia, even if excellent collateral circulation has been established [24]. Consequently, due to ischemic imbalance, patients with CTO are more prone to MI at the onset of an acute coronary event. Such attacks often lead to fatal consequences in patients with LVSD due to poor tolerance to ischemia [12].

Third, CTO accelerates the progression of cardiac function deterioration [22]. Because of the limited proliferative potential of cardiomyocytes, patients with LVSD and CTO may experience myocardial stunning and hibernation in response to recurrent episodes of ischemia. As ischemia progresses, there is a continual loss of cardiomyocytes, and the damaged myocardium cannot regenerate effectively. Instead, it develops fibrosis and scarring, ultimately leading to life-threatening complications such as heart failure, arrhythmia, and potentially death [22]. The adverse effects of CTO and LVSD subsequently translated into a higher risk of death. Survival analysis revealed that patients with LVSD and CTO had higher mortality during follow-up, with sudden cardiac death and end-stage heart failure being the leading causes of death [25,26].

Whether it involves relieving stenosis of the blood donor artery supplying the ischemic area or recanalizing the occluded native artery, the theoretical basis of revascularization for LVSD is to restore blood flow to the hypoperfused region of viable myocardium. This restoration can reverse left ventricular dysfunction, thereby reducing ischemic burden, reversing myocardial hibernation, reducing malignant arrhythmias, and preventing MI [27–29]. Therefore, revascularization therapy is important for improving the long-term prognosis of patients.

Data from the International Study of Comparative Health Effectiveness with Medical and Invasive Approaches (ISCHEMIA) trial revealed that patients with LVSD undergoing revascularization had lower all-cause mortality, cardiovascular mortality, and MI rates than those receiving conservative medical therapy [30]. Data from the Veterans Affairs Clinical Assessment, Reporting, and Tracking (VA CART) program compared the 3-year outcomes of PCI and medical treatment (MT) in patients with LVSD and observed a lower rate of all-cause rehospitalization or mortality in the PCI cohort [31]. The Surgical Treatment for Ischaemic Heart Failure (STICH) trial was a multicenter, open-label, randomized controlled trial that enrolled patients with LVSD and randomized them to CABG combined with MT or MT alone, with all-cause mortality as the primary outcome. No significant survival benefit of CABG was observed over a median follow-up of 56 months, which may have been partially negated by a significant increase in mortality 30 days post-CABG [32]. The STICHES trial, which prolonged the median follow-up to 9.8 years from the STICH trial, observed that CABG was associated with a sustained and significant decrease in all-cause mortality, cardiovascular mortality, death from any cause, and hospitalization for cardiovascular causes. CABG increased the median survival time in the STICHES trial by approximately 18 months and decreased the relative risk of all-cause mortality by 16% [27]. As convincing evidence, the STICH series has influenced the update of guidelines for CABG recommendation and has significantly impacted clinical decision-making. The improvement in long-term survival associated with CABG establishes a central role in the revascularization treatment of LVSD.

CABG is the most commonly performed procedure and the most intensively studied method in cardiac surgery. However, cardiologists must re-evaluate the significantly increased incidence of adverse events in patients with LVSD after CABG in the short term, as reported in the STICH trial [32]. Low LVEF is an essential component of many risk assessment systems for cardiac surgery [33,34]. In the EuroSCORE II risk algorithm, poor left ventricular function increased mortality during and early after cardiac surgery [34]. The Society of Thoracic Surgeons (STS) risk algorithm demonstrated that every 10% reduction in LVEF increased the risk of in-hospital mortality after CABG by 19% [33]. Seese *et al.* [35] also identified that cardiac surgery was associated with a higher rate of surgical death among patients with low LVEF, and a significant association existed between lower LVEF and an increased risk of postoperative death.

Although CABG remains the preferred method for revascularization of complex types of coronary heart disease, PCI has experienced significant expansion in its application in clinical practice [36,37]. In recent years, PCI has surpassed CABG in its proportion as the primary revascularization strategy for LVSD, and the growth trend is far beyond that of CABG [3,8]. However, poor cardiac function and complex coronary lesions pose distinct challenges to PCI in patients with LVSD and CTO. In the CathPCI registry mortality model, each 5% decrease in LVEF was associated with a 10% increased risk of post-PCI in-hospital mortality, while treatment with CTO increased the risk of post-PCI in-hospital mortality by 55% [38].

Few previous studies have compared the safety of PCI with that of CABG for revascularization in patients with LVSD. Bianco *et al.* [39] constructed a 1:1 propensity-matched cohort of patients with LVSD and observed no significant difference in 30-day mortality among patients undergoing PCI or CABG, implying that CABG can be performed without increasing the risk of short-term mortality. Chen *et al.* [28] compared the in-hospital outcomes of patients with LVSD treated with PCI or CABG and observed that CABG had a higher rate of in-hospital mortality than PCI; however, this difference was not statistically significant. An observational study examining in-hospital outcomes after revascularization of unprotected left main coronary artery disease revealed that the incidence of MACCE, all-cause mortality, and MI in the CABG group was higher than that in the PCI group. Multivariate analysis revealed that LVSD significantly increased the risk of in-hospital mortality, whereas CABG was the strongest risk factor for in-hospital mortality [36].

Selecting an appropriate revascularization strategy for patients with LVSD and CTO is challenging. Research comparing therapeutic strategies between various clinical subgroups of LVSD is scarce, and there remains insufficient published data on in-hospital outcomes for patients with LVSD and CTO [40,41]. Without clinical trial data, the safety of PCI or CABG in patients with LVSD and CTO remains unknown. This study is distinctive in examining the outcomes of high-risk patients who are typically excluded from routine trials. In this study, the incidence of in-hospital MACCE after revascularization in patients with LVSD and CTO was 3.2% and was significantly higher in the CABG group than in the PCI group (6.5% *vs*. 1.8%, $p < 0.001$), primarily due to all-cause mortality. In recently published data, the in-hospital mortality rates for patients with LVSD undergoing PCI and CABG were 0.8%–3.9% and 4.7%–6.7%, respectively [28,42–44]. Our findings corroborated previous research, indicating a significantly higher incidence of all-cause mortality in the CABG group than in the PCI group (4.3% *vs*. 1.5%, $p = 0.015$). Considering the influence of the duration of postprocedural hospital stay and other confounding factors, CABG was no longer significantly associated with in-hospital MACCE and all-cause mortality after IPTW. However, it remained linked to a higher risk of MI. Our study suggests that PCI provides a relatively safe opportunity for revascularization in patients with LVSD and CTO.

This study presents promising evidence that PCI is a safer periprocedural revascularization strategy for patients with LVSD and CTO. However, it also leads to a higher rate of incomplete revascularization. This is due to the challenges posed by diffuse coronary artery disease, complex coronary lesion features, burdensome comorbidities, and the risk of hemodynamic instability, which make achieving complete revascularization in these patients challenging. Recent studies have indicated that incomplete revascularization is closely associated with both short- and long-term adverse cardiovascular events [39,41,45,46]. Furthermore, incomplete revascularization raises the potential for subsequent procedures, and the cumulative risk of multiple PCI sessions increases uncertainty, affecting patients' preferences. Some patients may opt to endure the painful recovery period after CABG to avoid the need for repeat coronary revascularization. Conversely, others may prefer PCI despite the risk of incomplete revascularization and the potential for future procedures. Cardiologists should aim to identify the lowest-risk revascularization strategy within a patient-centered care model, considering the complex conditions and multiple factors involved when selecting a revascularization strategy. This requires extensive clinical experience, technical proficiency, and evidence-based medical data [9]. Currently, this gap remains unresolved.

Limitations

This study has several limitations. First, although IPTW was used to adjust for potential bias, the observational study was susceptible to unmeasured confounders. Second, although all cardiac center operators were required to perform standard procedures, uniform skill levels among all operators were not guaranteed. Lastly, the study was conducted at a high-volume cardiac center. Therefore, the conclusions should be interpreted cautiously when applied to other medical centers.

Conclusions

In conclusion, patients with LVSD and CTO exhibited a high risk of in-hospital adverse events associated with revascularization. The in-hospital MACCE following revascularization with PCI were comparable to those after CABG. However, PCI showed a lower risk of MI. Insights from this real-world study may aid heart teams in evaluating the benefits and risks, thereby supporting clinical decision-making for patients with LVSD and CTO. Further research is required to explore differences in periprocedural outcomes between PCI and CABG and to identify suitable candidates for revascularization.

Abbreviations

BMI, body mass index; CABG, coronary artery bypass grafting; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; CTO, chronic total occlusion; EuroSCORE II, European System for Cardiac Operative Risk Evaluation II; HDL, high-density lipoprotein; IPTW, inverse probability of treatment weighting; J-CTO, Multicenter CTO Registry of Japan; LAD, left anterior descending artery; LCX, left circumflex artery; LDL, low-density lipoprotein; LM, left main; LVEDD, left ventricular end-diastolic dimension; LVEF, left ventricular ejection fraction; LVESD, left ventricular end-systolic dimension; MI, myocardial infarction; NYHA, New York Heart Association; PCI, percutaneous coronary intervention; PROGRESS CTO, Prospective Global Registry for the Study of Chronic Total Occlusion Intervention; RCA, right coronary artery; SMD, standardized mean difference; STEMI, ST-segment elevation myocardial infarction; SYNTAX, SYNergy between percutaneous coronary intervention with TAXus and cardiac surgery; ULMCAD, unprotected left main coronary artery disease; VF, ventricular fibrillation; VT, ventricular tachycardia.

Availability of Data and Materials

The datasets supporting the conclusion of this article are available from the corresponding author on reasonable request.

Author Contributions

YZ: Writing—original draft, Writing—review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization. ZW: Writing—review & editing, Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization. SW: Writing—review & editing, Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization. JL: Writing—review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

The study was reviewed and approved by Ethics Committee of Beijing Anzhen Hospital (No.2023026X). Due to the retrospective design of this study, the requirement for written informed consent was exempted.

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Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.7637.

References

[1] Felker GM, Shaw LK, O'Connor CM. A standardized definition of ischemic cardiomyopathy for use in clinical research. Journal of the American College of Cardiology. 2002; 39: 210–218.

[2] Ahmad Y, Petrie MC, Jolicoeur EM, Madhavan MV, Velazquez EJ, Moses JW, *et al*. PCI in Patients With Heart Failure: Current Evidence, Impact of Complete Revascularization, and Contemporary Techniques to Improve Outcomes. Journal of the Society for Cardiovascular Angiography & Interventions. 2022; 1: 100020.

[3] Bollano E, Redfors B, Rawshani A, Venetsanos D, Völz S, Angerås O, *et al*. Temporal trends in characteristics and outcome of heart failure patients with and without significant coronary artery disease. ESC Heart Failure. 2022; 9: 1812–1822.

[4] Heidenreich PA, Bozkurt B, Aguilar D, Allen LA, Byun JJ, Colvin MM, *et al*. 2022 AHA/ACC/HFSA Guideline for the Management of Heart Failure: A Report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. Circulation. 2022; 145: e895–e1032.

[5] Neumann FJ, Sousa-Uva M, Ahlsson A, Alfonso F, Banning AP, Benedetto U, *et al*. 2018 ESC/EACTS Guidelines on myocardial revascularization. European Heart Journal. 2019; 40: 87–165.

[6] Virani SS, Newby LK, Arnold SV, Bittner V, Brewer LC, Demeter SH, *et al*. 2023 AHA/ACC/ACCP/ASPC/NLA/PCNA Guideline for the Management of Patients With Chronic Coronary Disease: A Report of the American Heart Association/American College of Cardiology Joint Committee on Clinical Practice Guidelines. Circulation. 2023; 148: e9–e119.

[7] Yamamoto K, Matsumura-Nakano Y, Shiomi H, Natsuaki M, Morimoto T, Kadota K, *et al*. Effect of Heart Failure on Long-Term Clinical Outcomes After Percutaneous Coronary Intervention Versus Coronary Artery Bypass Grafting in Patients With Severe Coronary Artery Disease. Journal of the American Heart Association. 2021; 10: e021257.

[8] Völz S, Redfors B, Angerås O, Ioanes D, Odenstedt J, Koul S, *et al*. Long-term mortality in patients with ischaemic heart failure revascularized with coronary artery bypass grafting or percutaneous coronary intervention: insights from the Swedish Coronary Angiography and Angioplasty Registry (SCAAR). European Heart Journal. 2021; 42: 2657–2664.

[9] Kirtane AJ, Doshi D, Leon MB, Lasala JM, Ohman EM, O'Neill WW, *et al*. Treatment of Higher-Risk Patients With an Indication for Revascularization: Evolution Within the Field of Contemporary Percutaneous Coronary Intervention. Circulation. 2016; 134: 422–431.

[10] Tajstra M, Pyka Ł, Gorol J, Pres D, Gierlotka M, Gadula-Gacek E, *et al*. Impact of Chronic Total Occlusion of the Coronary Artery on Long-Term Prognosis in Patients With Ischemic Systolic Heart Failure: Insights From the COMMIT-HF Registry. JACC. Cardiovascular Interventions. 2016; 9: 1790–1797.

[11] Simsek B, Rempakos A, Kostantinis S, Karacsonyi J, Rangan BV, Mastrodemos OC, *et al*. A Systematic Review of Periprocedural Risk Prediction Scores in Chronic Total Occlusion Percutaneous Coronary Intervention. The American Journal of Cardiology. 2023; 193: 118–125.

[12] Simsek B, Kostantinis S, Karacsonyi J, Alaswad K, Karmpaliotis D, Masoumi A, *et al*. Outcomes of chronic total occlusion percutaneous coronary intervention in patients with reduced left ventricular ejection fraction. Catheterization and Cardiovascular Interventions. 2022; 99: 1059–1064.

[13] Albaeni A, Chatila KF, Thakker RA, Kumfa P, Alwash H, Elsherbiny A, *et al*. In-Hospital Outcomes of Chronic Total Occlusion Percutaneous Coronary Interventions in Heart failure patients. Current Problems in Cardiology. 2023; 48: 101458.

[14] McDonagh TA, Metra M, Adamo M, Gardner RS, Baumbach A, Böhm M, *et al*. 2021 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure. European Heart Journal. 2021; 42: 3599–3726.

[15] Ybarra LF, Rinfret S, Brilakis ES, Karmpaliotis D, Azzalini L, Grantham JA, *et al*. Definitions and Clinical Trial Design Principles for Coronary Artery Chronic Total Occlusion Therapies: CTO-ARC Consensus Recommendations. Circulation. 2021; 143: 479–500.

[16] Garcia-Garcia HM, McFadden EP, Farb A, Mehran R, Stone GW, Spertus J, *et al*. Standardized End Point Definitions for Coronary Intervention Trials: The Academic Research Consortium-2 Consensus Document. European Heart Journal. 2018; 39: 2192–2207.

[17] Velazquez EJ. Percutaneous Coronary Intervention or Coronary Artery Bypass Grafting to Treat Ischemic Cardiomyopathy? JAMA Cardiology. 2020; 5: 641–642.

[18] Kobayashi N, Ito Y, Kishi K, Muramatsu T, Okada H, Oikawa Y, *et al*. Procedural results and in-hospital outcomes of percutaneous coronary intervention for chronic total occlusion in patients with reduced left ventricular ejection fraction: Sub-analysis of the Japanese CTO-PCI Expert Registry. Catheterization and Cardiovascular Interventions. 2022; 100: 30–39.

[19] Nombela-Franco L, Mitroi CD, Fernández-Lozano I, García-Touchard A, Toquero J, Castro-Urda V, *et al*. Ventricular arrhythmias among implantable cardioverter-defibrillator recipients for primary prevention: impact of chronic total coronary occlusion (VACTO Primary Study). Circulation. Arrhythmia and Electrophysiology. 2012; 5: 147–154.

[20] Nombela-Franco L, Iannaccone M, Anguera I, Amat-Santos IJ, Sanchez-Garcia M, Bautista D, *et al*. Impact of Chronic Total Coronary Occlusion on Recurrence of Ventricular Arrhythmias in Ischemic Secondary Prevention Implantable Cardioverter-Defibrillator Recipients (VACTO Secondary Study): Insights From Coronary Angiogram and Electrogram Analysis. JACC. Cardiovascular Interventions. 2017; 10: 879–888.

[21] Iannaccone M, Nombela-Franco L, Gallone G, Annone U, Di Marco A, Giannini F, *et al*. Impact of Successful Chronic Coronary Total Occlusion Recanalization on Recurrence of Ventricular Arrhythmias in Implantable Cardioverter-Defibrillator Recipients for Ischemic Cardiomyopathy (VACTO PCI Study). Cardiovascular Revascularization Medicine: Including Molecular Interventions. 2022; 43: 104–111.

[22] Liao R, Li Z, Wang Q, Lin H, Sun H. Revascularization of chronic total occlusion coronary artery and cardiac regeneration. Frontiers in Cardiovascular Medicine. 2022; 9: 940808.

[23] Behnes M, Mashayekhi K, Kuche P, Kim SH, Schupp T, von Zworowsky M, *et al*. Prognostic impact of coronary chronic total occlusion on recurrences of ventricular tachyarrhythmias and ICD therapies. Clinical Research in Cardiology. 2021; 110: 281–291.

[24] Sachdeva R, Agrawal M, Flynn SE, Werner GS, Uretsky BF. The myocardium supplied by a chronic total occlusion is a persistently ischemic zone. Catheterization and Cardiovascular Interventions. 2014; 83: 9–16.

[25] Toma A, Stähli BE, Gick M, Gebhard C, Kaufmann BA, Mashayekhi K, *et al*. Comparison of Benefit of Successful Percutaneous Coronary Intervention for Chronic Total Occlusion in Patients With Versus Without Reduced (≤40%) Left Ventricular Ejection Fraction. The American Journal of Cardiology. 2017; 120: 1780–1786.

[26] Ishida K, Martin-Yuste V, Prat S, Cardona M, Ferreira I, Sabaté M. Prognosis of Patients With Reduced Left Ventricular Ejection Fraction and Chronic Total Occlusion According to Treatment Applied. Cardiovascular Revascularization Medicine: Including Molecular Interventions. 2021; 27: 22–27.

[27] Velazquez EJ, Lee KL, Jones RH, Al-Khalidi HR, Hill JA, Panza JA, *et al*. Coronary-Artery Bypass Surgery in Patients with Ischemic Cardiomyopathy. The New England Journal of Medicine. 2016; 374: 1511–1520.

[28] Chen YW, Lee WC, Fang HY, Sun CK, Sheu JJ. Coronary Artery Bypass Graft Surgery Brings Better Benefits to Heart Failure Hospitalization for Patients with Severe Coronary Artery Disease and Reduced Ejection Fraction. Diagnostics. 2022; 12: 2233.

[29] Ryan M, Morgan H, Petrie MC, Perera D. Coronary revascularisation in patients with ischaemic cardiomyopathy. Heart. 2021; 107: 612–618.

[30] Lopes RD, Alexander KP, Stevens SR, Reynolds HR, Stone GW, Piña IL, *et al*. Initial Invasive Versus Conservative Management of Stable Ischemic Heart Disease in Patients With a History of Heart Failure or Left Ventricular Dysfunction: Insights From the ISCHEMIA Trial. Circulation. 2020; 142: 1725–1735.

[31] Brophy TJ, Warsavage TJ, Hebbe AL, Plomondon ME, Waldo SW, Rao SV, *et al*. Percutaneous coronary intervention in patients with stable coronary artery disease and left ventricular systolic dysfunction: insights from the VA CART program. American Heart Journal. 2021; 235: 149–157.

[32] Velazquez EJ, Lee KL, Deja MA, Jain A, Sopko G, Marchenko A, *et al*. Coronary-artery bypass surgery in patients with left ventricular dysfunction. The New England Journal of Medicine. 2011; 364: 1607–1616.

[33] Shahian DM, O'Brien SM, Filardo G, Ferraris VA, Haan CK, Rich JB, *et al*. The Society of Thoracic Surgeons 2008 cardiac surgery risk models: part 1–coronary artery bypass grafting surgery. The Annals of Thoracic Surgery. 2009; 88: S2–S22.

[34] Nashef SAM, Roques F, Sharples LD, Nilsson J, Smith C, Goldstone AR, *et al*. EuroSCORE II. European Journal of Cardio-thoracic Surgery. 2012; 41: 734–744; discussion 744–745.

[35] Seese L, Sultan I, Gleason T, Wang Y, Thoma F, Navid F, *et al*. Outcomes of Conventional Cardiac Surgery in Patients With Severely Reduced Ejection Fraction in the Modern Era. The Annals of Thoracic Surgery. 2020; 109: 1409–1418.

[36] Daoulah A, Alasmari A, Hersi AS, Alshehri M, Garni TA, Abuelatta R, *et al*. Percutaneous Coronary Intervention Vs Coronary Artery Bypass Surgery for Unprotected Left Main Coronary Disease: G-LM Registry. Current Problems in Cardiology. 2022; 47: 101002.

[37] Lin S, Guan C, Wu F, Xie L, Zou T, Shi Y, *et al*. Coronary Artery Bypass Grafting and Percutaneous Coronary Intervention in Patients With Chronic Total Occlusion and Multivessel Disease. Circulation. Cardiovascular Interventions. 2022; 15: e011312.

[38] Brennan JM, Curtis JP, Dai D, Fitzgerald S, Khandelwal AK, Spertus JA, *et al*. Enhanced mortality risk prediction with a focus on high-risk percutaneous coronary intervention: results from 1,208,137 procedures in the NCDR (National Cardiovascular Data Registry). JACC. Cardiovascular Interventions. 2013; 6: 790–799.

[39] Bianco V, Kilic A, Mulukutla S, Gleason TG, Kliner D, Allen CC, *et al*. Percutaneous coronary intervention versus coronary artery bypass grafting in patients with reduced ejection fraction. The Journal of Thoracic and Cardiovascular Surgery. 2021; 161: 1022–1031.e5.

[40] Cabac-Pogorevici I, Muk B, Rustamova Y, Kalogeropoulos A, Tzeis S, Vardas P. Ischaemic cardiomyopathy. Pathophysiological insights, diagnostic management and the roles of revascularisation and device treatment. Gaps and dilemmas in the era of advanced technology. European Journal of Heart Failure. 2020; 22: 789–799.

[41] Parikh PB, Bhatt DL, Bhasin V, Anker SD, Skopicki HA, Claessen BE, *et al*. Impact of Percutaneous Coronary Intervention on Outcomes in Patients With Heart Failure: JACC State-of-the-Art Review. Journal of the American College of Cardiology. 2021; 77: 2432–2447.

[42] Ji Q, Xia LM, Shi YQ, Ma RH, Shen JQ, Ding WJ, *et al*. Impact of severe left ventricular dysfunction on in-hospital and mid-term outcomes of Chinese patients undergoing first isolated off-pump coronary artery bypass grafting. Journal of Cardiothoracic Surgery. 2017; 12: 87.

[43] Yan P, Zhang K, Cao J, Dong R. Left Ventricular Structure is Associated with Postoperative Death After Coronary Artery Bypass Grafting in Patients with Heart Failure with Reduced Ejection Fraction. International Journal of General Medicine. 2022; 15: 53–62.

[44] Wallace TW, Berger JS, Wang A, Velazquez EJ, Brown DL. Impact of left ventricular dysfunction on hospital mortality among patients undergoing elective percutaneous coronary intervention. The American Journal of Cardiology. 2009; 103: 355–360.

[45] Wu X, Cai J, Zhang Q, Huang H. Assessing the Clinical Influence of Chronic Total Occlusions (CTOs) Revascularization and the Impact of Vascularization Completeness on Patients with Left Ventricular (LV) Systolic Dysfunction. Computational Intelligence and Neuroscience. 2022; 2022: 9128206.

[46] Pinto G, Fragasso G, Gemma M, Bertoldi L, Salerno A, Godino Md C, *et al*. Long-term clinical effects of recanalization of chronic coronary total occlusions in patients with left ventricular systolic dysfunction. Catheterization and Cardiovascular Interventions. 2020; 96: 831–838.