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Hybrid algorithm CTO-PCI in a Resource-Constrained Tunisian Center

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Research Article

Keywords: Chronic Total Occlusion, Percutaneous Coronary Intervention,Angina, Prognosis

Posted Date: April 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9113443/v1

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Additional Declarations: No competing interests reported.

Abstract

Background: Evidence on chronic total occlusion percutaneous coronary intervention (CTO-PCI) from North Africa remains scarce, with limited data on procedural outcomes and patient-centred endpoints in resource-constrained settings.

Methods: Prospective single-centre study of 114 patients undergoing 134 CTO-PCI procedures (2022-2024) at Farhat Hached University Hospital, Tunisia. CTOs were treated using contemporary hybrid algorithms. Technical success required TIMI 3 flow with <30% residual stenosis. Primary endpoint: immediate outcomes and technical success predictors. Secondary endpoints: 12-month major adverse cardiac/cerebrovascular events (MACCE), target lesion failure (TLF), and symptom improvement (CCS/NYHA class). Multivariable logistic regression identified technical failure predictors.

Results: Mean age was 60.9±9.1 years; 84.2% male. High-risk features included diabetes (60.5%), smoking (72.8%), and severe LVEF≤35% (20.2%). Median J-CTO score was 2 (IQR 1-3). Technical success was 82.1%, improving from 66.7% (2022) to 88.8% (2024; p=0.011). Independent technical failure predictors were J-CTO≥3 (OR 4.07, 95%CI 1.53-10.88) and LVEF≤35% (OR 3.90, 95%CI 1.38-11.04). In-hospital MACCE was 2.6%; periprocedural complications 14.2% (major: 4.5%). At 12 months, MACCE was 13.2% (86.3% MACCE-free survival); TLF 2.6%. Successful CTO-PCI predicted lower MACCE (8.7% vs 60%, p<0.001) and superior symptomatic improvement at 12 months, with marked reductions in CCS and NYHA class compared with technical failure (p=0.013 and p=0.011, respectively).

Conclusions: Structured hybrid CTO-PCI in a North African centre achieved registry-comparable technical success (82.1%) and safety despite higher-risk patients and resource limits. Success strongly associated with mid-term event reduction and substantial symptom improvement, supporting scalability of modern CTO programs in emerging economies.

Introduction

Chronic total occlusion (CTO), defined as a complete coronary artery obstruction with TIMI 0 flow of presumed duration ≥ 3 months, represents one of the most complex subsets of coronary artery disease. CTOs are identified in approximately 15–20% of patients undergoing coronary angiography and are particularly prevalent among individuals with ischemic cardiomyopathy and reduced left ventricular ejection fraction [1–3].

Percutaneous coronary intervention for CTO (CTO-PCI) remains technically demanding and has historically been associated with lower procedural success rates and increased complication risk compared with non-occlusive lesions [4]. Over the past decade, however, advances in dedicated devices, refinement of antegrade and retrograde techniques, and structured hybrid approach implementation have markedly improved success rates in experienced centres [5].

Although composite event-based outcomes such as major adverse cardiac and cerebrovascular events (MACCE) are commonly reported, symptom relief and functional improvement remain the primary clinical drivers for CTO revascularisation [6]. Contemporary guidelines therefore recommend CTO-PCI mainly in patients with persistent angina despite optimal medical therapy and objective evidence of ischemia or viability in the CTO-related territory [7].

Despite these advances, most available data originate from North American, European, or East Asian registries. Evidence from North Africa is extremely limited, and prospective evaluations of procedural and technical success, safety, and patient-centred outcomes in Tunisian populations are scarce. Differences in demographic characteristics, comorbidity burden, healthcare resources, and interventional practice patterns may influence outcomes and limit the generalisability of international data to this region [8].

Farhat Hached University Hospital in Sousse has developed a dedicated CTO program with progressive adoption of contemporary revascularisation strategies. Evaluating outcomes from this centre provides an opportunity to generate locally relevant data and to benchmark Tunisian results against established international registries.

To address this regional evidence gap, we conducted a prospective observational study between January 2022 and December 2024 to evaluate real-world outcomes of CTO-PCI in a Tunisian cohort. The primary objective was to assess immediate procedural outcomes and determinants of technical success. The secondary objective was to evaluate twelve-month clinical and functional outcomes, including MACCE, target lesion failure, and changes in angina severity.

Methods

We prospectively analysed 114 patients who underwent 134 CTO-PCI procedures between 1 January 2022 and 31 December 2024 at the Cardiology Department of Farhat Hached University Hospital, Sousse, Tunisia. Data were collected in real time using standardised case report forms and cross-verified against medical and catheterisation laboratory records.

CTO was defined according to CTO-ARC criteria as angiographic TIMI 0 antegrade flow with an estimated duration ≥ 3 months. Indications for CTO-PCI were consistent with contemporary ESC and Euro-CTO recommendations and were confirmed following multidisciplinary evaluation [7]. Patients were eligible if aged 18–85 years with angiographically confirmed CTO and guideline-based indications, including persistent angina despite optimal medical therapy, objective ischaemia (≥ 10% of left ventricular myocardium), or evidence of viable myocardium in the CTO territory [1, 7]. Selected ST-segment elevation myocardial infarction patients with concomitant non-infarct-related artery CTO undergoing complete revascularisation were also included [1]. Written informed consent was obtained from all participants. Exclusion criteria comprised non-viable myocardium, cardiogenic shock, contraindication to dual antiplatelet therapy or iodinated contrast, and inability to complete follow-up. Baseline variables included demographics, cardiovascular risk factors, prior cardiac events, renal

function, and clinical presentation. Symptom severity was assessed using the Canadian Cardiovascular Society (CCS) angina classification and the New York Heart Association (NYHA) functional class [9, 10]. Left ventricular ejection fraction was measured using Simpson's method and categorised as preserved (≥ 50%), moderately reduced (35–50%), or severely reduced (≤ 35%). Coronary angiograms were independently reviewed by two experienced operators. Recorded variables included target vessel, lesion morphology, calcification, collateral grade (Werner classification), and lesion complexity assessed using the J-CTO score (< 3 vs ≥ 3) [11, 12]. CTO-PCI was performed using a contemporary hybrid strategy allowing transition between antegrade and retrograde techniques. Access site, crossing strategy, devices used, procedure duration, fluoroscopy time, and contrast volume were documented. Technical success was defined as restoration of TIMI 3 antegrade flow with < 30% residual stenosis [1]. Procedural success was defined as technical success without in-hospital major adverse cardiac and cerebrovascular events (MACCE) [1]. In-hospital MACCE, assessed at patient level, included death, stroke, myocardial infarction, or urgent repeat revascularisation. Major procedural complications, assessed at procedure level, included peri-procedural death, stroke, myocardial infarction, collateral perforation with tamponade, acute stent thrombosis, donor vessel dissection, and major vascular complications. Patients were systematically followed for twelve months. The primary endpoint was immediate technical and procedural success and its determinants. Secondary endpoints included twelve-month MACCE, target lesion failure, and change in CCS and NYHA class, with clinical improvement defined as a reduction of at least one class. Statistical analyses were performed using IBM SPSS Statistics version 25.0. Normality was assessed using the Shapiro–Wilk test. Continuous variables were compared using Student's t-test for normally distributed data or the Mann–Whitney U test for non-normal distributions. Categorical variables were analysed using the χ^2 test or Fisher's exact test as appropriate. Paired pre- and post-procedural comparisons of CCS and NYHA class were performed using the Wilcoxon signed-rank test. Kaplan–Meier analysis was used to estimate MACCE-free and target lesion failure-free survival, with comparisons performed using the log-rank test. Patients were censored at the time of last follow-up or event occurrence. Variables with $p < 0.20$ in univariate analysis that were considered clinically relevant were entered into a multivariable logistic regression model to identify independent predictors of technical success. Results are reported as odds ratios with 95% confidence intervals. All statistical tests were two-sided, and a p-value < 0.05 was considered statistically significant.

Results

During the study period, 114 patients underwent 134 CTO-PCI procedures involving 121 CTO lesions. Overall catheterisation laboratory activity increased substantially, with CTO-PCI procedures rising from 18 in 2022 to 80 in 2024, representing approximately 7% of all PCI procedures in the final year.

Baseline clinical characteristics are summarised in Table. Stable angina was the predominant presentation (76.3%) with most patients experiencing high symptom burden per Canadian Cardiovascular Society (CCS) grading, predominantly CCS III (59.8%) and CCS IV (18.4%). A small proportion (2.6%) were asymptomatic for angina but presented with dyspnoea. Among clinically stable patients, angina severity was predominantly moderate to severe, with 78.2% classified as CCS class III–

IV. Functional limitation was less pronounced, with 21.8% in NYHA class III–IV. Left ventricular systolic function was preserved (LVEF ≥ 50%) in 52.6% of patients, moderately reduced (35–50%) in 27.2%, and severely reduced (≤ 35%) in 20.2%, with a mean LVEF of 43.9 ± 12.9%. Regional wall motion assessment showed hypokinesia in 71.1% of CTO territories, normal motion in 25.6%, and akinesia in 3.3%, with no dyskinesia observed.

Angiographic characteristics of the included patients are summarised in Table 2. Multivessel coronary artery disease (≥ 2 diseased vessels) was identified in 86 patients (75.4%).

Table 1
Baseline clinical characteristics of the included patients according to technical success

Variable	Overall (N = 114)	Not successful (n = 10)	Successful (n = 104)	p value
Age (years)	60.9 ± 9.1	64.6 ± 10.1	60.5 ± 9.0	0.17
Male gender	96 (84.2%)	8 (80.0%)	88 (84.6%)	0.70
Current smoker and former smoker	83 (72.8%)	4 (40.0%)	79 (76.0%)	**0.002**
Diabetes mellitus (NID/ID)	69 (60.5%)	8 (80.0%)	61 (58.7%)	0.19
Hypertension	66 (57.9%)	5 (50.0%)	61 (58.7%)	0.60
Dyslipidaemia	79 (69.3%)	6 (60.0%)	73 (70.2%)	0.51
Obesity	14 (12.3%)	0 (0.0%)	14 (13.5%)	0.22
Peripheral arterial disease	24 (21.1%)	1 (10.0%)	23 (22.1%)	0.37
COPD	5 (4.4%)	0 (0.0%)	5 (4.8%)	1.000
Renal failure on dialysis	2 (1.8%)	0 (0.0%)	2 (1.9%)	0.66
Prior stroke	3 (2.6%)	0 (0.0%)	3 (2.9%)	1.000
Clinical presentation				
Stable angina	80 (70.2%)	5 (50.0%)	75 (72.1%)	0.31
ACS (UA + MI)	29 (25.4%)	4 (40.0%)	25 (24.0%)	
Dyspnoea	5 (4.4%)	1 (10.0%)	4 (3.9%)	
Prior PCI/CABG/MI history				
Previous myocardial infarction (overall)	72 (63.2%)	7 (70.0%)	65 (62.5%)	0.64
Previous MI in CTO territory	29 (25.4%)	4 (40.0%)	25 (24.0%)	0.27
Previous PCI	68 (59.6%)	6 (60.0%)	62 (59.6%)	0.98
Previous PCI in CTO territory (re-occlusion)	17 (14.9%)	1 (10.0%)	16 (15.4%)	0.65
Previous CABG	6 (5.3%)	1 (10.0%)	5 (4.8%)	0.48
Previous CABG in CTO territory	5 (4.4%)	1 (10.0%)	4 (3.8%)	0.36
Left Ventricular Ejection Fraction (LVEF)				
≤ 35%	23 (20.2%)	4 (40.0%)	19 (18.3%)	**0.010**

Variable	Overall (N = 114)	Not successful (n = 10)	Successful (n = 104)	p value
> 35%	91 (79.8%)	6 (60.0%)	85 (81.7%)	

ACS: Acute coronary syndrome. UA: Unstable angina. MI: Myocardial infarction. STEMI: ST-segment elevation myocardial infarction. NSTEMI: Non–ST segment elevation myocardial infarction. COPD: Chronic obstructive pulmonary disease. BMI: Body mass index. CABG: Coronary artery bypass graft surgery. CTO: Chronic total occlusion. PCI: Percutaneous coronary intervention. LVEF: Left ventricular ejection fraction.

Table 2
Angiographic characteristics of the included patients according to technical success

Variable	Category / Value	Overall (N = 134)	Not successful (n = 24)	Successful (n = 110)	p value
Number of diseased vessels (including CTO)	1 vessel	28 (24.6%)	2 (20.0%)	26 (25.0%)	0.74
	2 vessels	42 (36.8%)	3 (30.0%)	26 (25.0%)	
	3 vessels	44 (38.6%)	5 (50.0%)	39 (37.5%)	
CTO artery	LMT	3 (2.2%)	1 (4.2%)	2 (1.8%)	0.637
	LAD	63 (47.01%)	14 (58.3%)	49 (44.5%)	
	LCx	14 (10.44%)	2 (8.3%)	12 (10.9%)	
	RCA	52 (38.8%)	7 (29.2%)	45 (40.9%)	
	SB	2 (1.4%)	0 (0%)	2 (1.8%)	
CTO location	Ostial	15 (11.2%)	4 (16.7%)	11 (1%)	0.710
	Proximal	53 (39.6%)	10 (41.7%)	43 (39%)	
	Mid	60 (44.8%)	9 (37.5%)	51 (46.4%)	
	Distal	6 (4.5%)	1 (4.2%)	5 (0.45%)	
In-stent CTO		16 (11.9%)	1 (4.2%)	15 (13.6%)	0.195
> 1 CTO segment		49 (36.6%)	9 (37.5%)	40 (36.4%)	0.917
Bifurcation involvement		64 (47.8%)	10 (41.7%)	54 (49.0%)	0.509
Occlusion duration (months), median [IQR]		12 [6–17]	12 [6–24]	9 [6–15]	0.278
CTO length (mm), median [IQR]		25 [18–40]	25 [20–41]	25 [15–40]	0.600
CTO length > 20 mm		92 (68.7%)	18 (75%)	74 (67.3%)	0.460
CTO bend ≥ 45°		64 (47.8%)	13 (54.2%)	51 (46.4%)	0.488
Blunt stump or no stump		66 (49.3%)	16 (66.7%)	50 (45.5%)	**0.060**
Proximal tortuosity (moderate–severe)		13 (9.7%)	3 (12.5%)	10 (9.1%)	0.609
Moderate/Severe calcification		52 (38.8%)	17 (70.8%)	35 (31.8%)	**< 0.001**

Variable	Category / Value	Overall (N = 134)	Not successful (n = 24)	Successful (n = 110)	p value
Severe Distal vessel disease		57 (42.9%)	14 (58.3%)	43 (39.1%)	0.055
Collateral circulation	CC0-CC1	55 (41%)	14 (58%)	41 (37%)	**0.057**
	CC2-CC3	79 (59.0%)	10 (41.7%)	69 (62.7%)	
J-CTO score, median [IQR]		2 [1–3]	3 [2–4]	2 [1–3]	**0.006**

CTO: Chronic total occlusion. **RCA**: Right coronary artery. **LAD**: Left anterior descending artery. **LCx**: Left circumflex artery. **LMT**: Left main trunk. **CABG**: Coronary artery bypass grafting. **PCI**: Percutaneous coronary intervention. **MI**: Myocardial infarction. **CC**: Werner grading. **J-CTO**: Japanese Chronic Total Occlusion score.

Procedural characteristics of the included patients are summarised in Table 3. The final crossing wire most frequently belonged to the Fielder, Gaia families, and Gladius wires (Fig. 1). Stent implantation was performed in 97.2% of successful procedures, with a median of 1 stent per lesion [IQR 1–2] and a median total stent length of 49 mm [IQR 40–69]. Drug coated balloons were used in 10.9% of successful cases, mainly in combination with stenting.

Table 3
Procedural characteristics of the included patients according to technical success

Variable	Category / Value	Overall (N = 134)	CTO failure (n = 24)	CTO success (n = 110)	p value
Guiding catheter size	6F	33 (24.6%)	6 (25%)	27 (24.5%)	1.000
	7F	94 (70.1%)	17 (70.8%)	77 (70%)	
	≥ 7.5F	7 (5.2%)	1 (4.1%)	6 (85.7%)	
Access site	Radial	98 (73.1%)	15 (62.5%)	83 (75.5%)	0.195
	Femoral	36 (26.9%)	9 (37.5%)	27 (24.54%)	
Dual injection		103 (76.9%)	18 (75%)	85 (77.27%)	0.811
Final crossing strategy	Primarily antegrade	84 (62.7%)	11 (45.8%)	73 (66.36%)	0.06
	Primarily retrograde	9 (6.7%)	2 (8.3%)	7 (6.36%)	0.727
	Hybrid	41 (30.6%)	11 (45.8%)	30 (27.3%)	0.074
Previous CTO attempt	36 (26.9%)		7 (29.2%)	29 (26.4%)	0.78
Guide extension catheter	13 (9.7%)		3 (12.5%)	10 (9.1%)	0.61
IVUS use	3 (2.2%)		1 (4.2%)	2 (1.8%)	0.481
Rotational atherectomy	5 (3.7%)		0 (0%)	5 (4.5%)	0.287
Dual-lumen microcatheter	4 (3.0%)		1 (4.2%)	3 (2.7%)	0.707
Microcatheter use	113 (84.3%)		21 (87.5%)	92 (83.6%)	0.765
Tapered guidewire	100 (74.62%)		17 (70.8)	83 (75.5)	0.64
Total number of guidewires, median [IQR]	3 [2–4]		4 [3–6]	3 [2–4]	**0.006**
Procedural time (min) median [IQR]	120 [83.8–180]		150 [120–227.5]	120 [75.8–180]	**0.005**
Crossing time (min) median [IQR]	20 [5–50]		0 [0–33.8]	28.5 [10.8–54]	**< 0.001**
Fluoroscopy time (min) median [IQR]	48 [30–81]		65.2 [48.7–110.5]	41 [28.8–71.3]	**0.006**
Contrast volume (ml) median [IQR]	180 [150–200]		190 [150–260]	180 [150–200]	0.228

Variable	Category / Value	Overall (N = 134)	CTO failure (n = 24)	CTO success (n = 110)	p value
Air kerma (mGy) median [IQR]	1993 [1180–3085]		2811 [1993–3628]	1890 [1081–2872]	**0.010**
Dose-area product (Gy·cm²) median [IQR]	11922 [7106–20802]		18323 [10488–20802]	11515 [7106–20223]	0.09

CTO: Chronic total occlusion. **IVUS**: Intravascular ultrasound. **Gy·cm²**: Gray–square centimetre. **mGy**: Milligray.

A primary antegrade strategy was planned in 62.7% of procedures, and a primary retrograde strategy in 6.7%. The final successful crossing strategy remained primary antegrade in 62.7% of cases; however, strategy transition occurred frequently, reflecting implementation of a hybrid approach in 30.6% of cases. Successful antegrade recanalization was achieved in approximately 70% of antegrade attempts, including 50.8% via AWE and 10% via ADR. Among procedures requiring a retrograde approach (n = 50), retrograde wire crossing was achieved in 56%, with reverse CART employed in 38% of retrograde attempts. Septal collaterals constituted the predominant retrograde pathway (84%), most commonly CC2 collaterals (62%).

Technical success was achieved in 110 procedures (82.1%), with TIMI 3 flow restoration in all successful cases. Overall procedural success was 81.3%. The primary mechanism of failure was inability to cross the occlusion with a guidewire (15.7%). Technical success improved significantly over time, increasing from 66.7% in 2022 to 88.8% in 2024 (linear-by-linear association $\chi^2 = 6.40$, $p = 0.011$). Periprocedural complications occurred in 19 procedures (14.2%), corresponding to 24 total events, including 6 major complications (4.5%). Haemodynamic instability requiring catecholamine support was the most frequent complication (6.7%). Side-branch occlusion ≥ 2.5 mm occurred in 4.5%, stroke in 1.5%, coronary perforation without tamponade in 0.7%, donor artery dissection in 2.2%, and contrast-associated acute kidney injury in 2.2%. In-hospital MACCE occurred in 3 of 114 patients (2.63%). No urgent repeat revascularisation was recorded.

Failed procedures were associated with moderate-to-severe calcification (70.8% vs 31.8%, $p < 0.001$), higher J-CTO score (median 3 vs 2, $p = 0.006$), poor collateral circulation ($p = 0.057$), and severely reduced LVEF ≤ 35% (40.0% vs 18.3%, $p = 0.010$). In multivariable analysis, the clinically relevant independent predictors of technical failure were J-CTO score ≥ 3 (OR 4.07, 95% CI 1.53–10.88, $p = 0.005$) and LVEF ≤ 35% (OR 3.90, 95% CI 1.38–11.04, $p = 0.010$).

Follow-up was available for 73% of patients at twelve months. Median follow-up duration was 22 months [IQR 11–35]. MACCE occurred in 15 patients (13.2%), including 7 deaths and 8 myocardial infarctions. All-cause mortality was 6.1%. Kaplan–Meier analysis showed a twelve-month MACCE-free survival of 86.3% (95% CI 79.8–92.8%). MACCE incidence was significantly higher in patients with technical failure (60% vs 8.7%, log-rank $p < 0.001$). Reduced LVEF (≤ 35%) was associated with lower MACCE-free survival

(log-rank p = 0.038). Target lesion failure occurred in 3 patients (2.6%), with a twelve-month TLF-free survival of 97.1% (95% CI 93.8–100.0%). No significant differences were observed according to LVEF category or technical success.

Among symptomatic patients with paired follow-up data, significant improvement in angina severity was observed at twelve months. CCS class improved in 66 patients (81.5%) ($p < 0.001$), and NYHA functional class improved in 42 patients (51.9%) ($p < 0.001$). At twelve months, patients with successful CTO-PCI had significantly lower CCS class (median 1.0 vs 3.0, $p = 0.013$) and NYHA class (median 1.0 vs 2.0, $p = 0.011$) compared with those with technical failure.

Discussion

This prospective single-centre study describes the early evolution of a CTO-PCI programme in a North African low- to middle-income centre. Across 134 procedures, technical success reached 82.1% and improved significantly over time, approaching 90% in the final year, consistent with a learning-curve effect. Lesion complexity (J-CTO ≥ 3) and severely reduced left ventricular ejection fraction (LVEF ≤ 35%) independently predicted technical failure. Periprocedural complication rates were acceptable, and twelve-month MACCE-free survival and symptomatic improvement were substantial. These findings demonstrate that structured CTO-PCI programmes can achieve registry-comparable outcomes in emerging centres despite intermediate-to-high anatomical complexity.

Compared with contemporary international CTO registries, the Farhat Hached cohort reflects a higher-risk clinical profile despite broadly comparable demographic characteristics. Mean age (60.9 ± 9.1 years) was similar to that reported in MENATA (≈ 61 years) and PROGRESS-CTO cohorts (≈ 65years) [13, 14]. Male predominance (84.2%) was also consistent with global CTO populations, where male representation typically exceeds 80% [15, 16].

However, the burden of cardiovascular risk factors was notable. Diabetes mellitus was present in 60.5% of patients—substantially higher than rates reported in many Western registries (typically 35–45%) and slightly higher than MENATA [13–15, 17]. Smoking prevalence (72.8%) was likewise elevated compared with European datasets [18]. These findings likely reflect regional epidemiology and may contribute to greater diffuse coronary disease and calcification burden.

A history of prior myocardial infarction (60.5%) and prior PCI (57.0%) mirrored rates reported in expert registries, reflecting established coronary disease and prior revascularisation exposure. In contrast, prior coronary artery bypass grafting was uncommon (5.3%), similar to contemporary datasets [13, 15]

Mean LVEF (43.9%) was lower than typically described in selected randomised CTO trials and cohorts. Severe LV dysfunction (LVEF ≤ 35%) was present in 20.2% of patients, markedly higher than proportions reported in ERCTO (7.6%) and OPEN-CTO (13.7%), suggesting inclusion of a more clinically vulnerable population [15, 19].

Regarding clinical presentation, stable angina predominated (76.3%), consistent with elective CTO practice in OPEN-CTO, PROGRESS-CTO, and MENATA cohorts [13–15]. Importantly, angina severity was substantial at baseline, with 78.2% classified as CCS III–IV, representing a higher symptomatic burden than reported in OPEN-CTO (72.4%) and PROGRESS-CTO (63.6%). These features position the cohort as clinically higher-risk compared with many Western series and provide essential context for interpreting procedural success and mid-term outcomes.

From an angiographic perspective, target vessels' distribution differed from several international datasets. Whereas OPEN-CTO, PROGRESS-CTO, EURO-CTO, and MENATA registries reported right coronary artery predominance (55–64%), the Farhat Hached cohort demonstrated a higher proportion of left anterior descending (LAD) CTOs (47%). This distinction is clinically relevant, as LAD CTOs subtend a larger myocardial territory and may carry greater prognostic implications [13–16]. Median J-CTO score was 2 (IQR 1–3), indicating intermediate lesion complexity, comparable to MENATA (≈ 2.1) and PROGRESS-CTO (2.43 ± 1.30), and higher than that observed in the EURO-CTO PCI arm (1.82 ± 1.07), reflecting the inclusion of a less selected and anatomically more complex cohort [13–16]. Lesion length (median 25 mm) was slightly shorter than MENATA (≈ 30 mm), although moderate-to-severe calcification was observed in 38.8% of lesions, exceeding rates in several western and regional registries and suggesting a greater burden of advanced atherosclerosis [14, 16, 20]. Bifurcation involvement (47.8%) was also frequent and higher than reported in ERCTO, reinforcing anatomical complexity [20]. Collateral patterns were broadly comparable to international experience, with CC2–3 collaterals present in approximately 59% of cases, similar to PROGRESS-CTO (56.7%) but lower than ERCTO (89.7%) [13, 20]. In-stent CTO prevalence (11.9%) was lower than in some international cohorts, suggesting predominance of de novo occlusions [14, 21]. Overall, the angiographic profile aligns with contemporary real-world CTO practice and supports interpretation of procedural success within an appropriate anatomical framework.

Radial access predominated in the Farhat Hached cohort (73.1%), exceeding rates reported in major CTO registries and reflecting strong radial proficiency even in complex lesions [13, 14, 20]. Dual arterial injection was frequently employed (76.9%), consistent with contemporary European practice and supporting optimal lesion visualisation [16, 20]. An antegrade-first strategy remained dominant (≈ 63%), while retrograde techniques were used in over one-third of procedures, aligning with modern hybrid practice patterns. Hybrid strategy adoption (30.6%) demonstrates adherence to contemporary CTO algorithms and likely contributed to the progressive improvement in technical success observed over time.

Technical success (82.1%) aligns with contemporary real-world CTO registries, though slightly lower than large expert cohorts such as PROGRESS-CTO (≈ 87%) and the Japanese CTO-PCI Expert Registry (≈ 92%) [13, 21]. Compared with MENATA (≈ 91%), the modest difference may reflect multicentre expert participation and broader access to intravascular imaging [14]. Nevertheless, lesion complexity was comparable across cohorts, supporting the feasibility of CTO-PCI in a North African middle-income setting.

High lesion complexity (J-CTO ≥ 3) independently predicted technical failure (OR 4.07), aligning with PROGRESS-CTO findings showing a two-fold increase in failure per point increase in J-CTO score and supported by meta-analytic data validating its strong predictive value for procedural difficulty. [11, 22]. Severely reduced left ventricular function (LVEF ≤ 35%) also independently predicted failure (OR 3.90). Although expert registries report similar technical success across LVEF strata, patients with impaired ventricular function consistently exhibit higher clinical risk [23]. The higher prevalence of severe systolic dysfunction in the Farhat Hached cohort, combined with limited access to routine mechanical circulatory support, may explain its procedural impact in this setting. Thus, in middle-income centres, ventricular dysfunction may exert a more tangible influence on technical outcome than in high-volume expert institutions

In-hospital MACCE (2.6%) falls within the 1.7–3% range reported in PROGRESS-CTO and ERCTO registries [13, 20]. Although overall periprocedural complications were numerically higher (14.2%), this reflects comprehensive event capture, whereas registry definitions vary. Major complications (4.5%) remain within contemporary real-world ranges (3–10%) [24, 25]. Thus, procedural safety was comparable to international standards despite intermediate-to-high lesion complexity and limited intravascular imaging utilisation.

At twelve months, MACCE occurred in 13.2% of patients. This rate is comparable to mid-term event rates reported in OPEN-CTO (≈ 10%) and other all-comer registries, though higher than the 5.2% reported in the EURO-CTO PCI arm, which included more selected populations [15, 16]. Kaplan–Meier analysis demonstrated significantly lower event rates among patients with successful recanalization, mirroring findings from PROGRESS-CTO, where lower MACE rates were observed following successful CTO recanalization compared with technical failure [26]. These findings reinforce the clinically meaningful association between technical success and improved mid-term outcomes. Target lesion failure (2.6%) was consistent with contemporary drug-eluting stent performance and comparable to TLR/TLF rates reported in EURO-CTO and RECHARGE registries [16, 27].

Symptomatic improvement was substantial and clearly success-dependent, with 81.5% of patients demonstrating CCS improvement at twelve months. This parallels the EURO-CTO randomised trial, which showed significant angina reduction and improved quality of life following CTO-PCI compared with optimal medical therapy [16]. Although symptom assessment in EURO-CTO relied on validated patient-reported instruments rather than CCS or NYHA classification, the overall pattern of benefit closely mirrors the present findings. Further concordance is seen in the UK hybrid CTO experience reported by Wilson et al., where 88% of successfully treated patients were free of angina or minimally symptomatic at twelve months [28]. Unlike the MENATA regional dataset, our study incorporated structured CCS and NYHA follow-up, providing patient-centred outcome data beyond angiographic success [14].

Within the national context, the Farhat Hached cohort demonstrated higher rates of severe LV dysfunction and greater lesion complexity compared with La Rabta and Habib Thameur CTO cohorts. Despite this, technical success was numerically higher (82.1% vs 79.3% and 69.2%). Greater adoption of

dual access, microcatheters, and hybrid escalation strategies likely contributed to these differences. Importantly, Farhat Hached is the only Tunisian cohort to provide systematic twelve-month MACCE and symptom follow-up, enabling assessment of sustained clinical benefit beyond procedural metrics [29, 30].

Data on CTO-PCI from North Africa remain scarce. This study provides prospective real-world evidence demonstrating that structured hybrid CTO-PCI can achieve registry-level safety and efficacy in a low- to middle-income healthcare setting. Despite inclusion of higher-risk patients and resource constraints, outcomes approached those of established international registries, supporting expansion of contemporary CTO programmes in similar environments.

Conclusion

In this prospective single-centre study, implementation of a contemporary hybrid CTO-PCI programme in a North African low- to middle-income centre achieved technical success rates comparable to major international registries despite a clinically higher-risk population with elevated diabetes prevalence, substantial symptomatic burden, and frequent severe left ventricular dysfunction. Technical success improved significantly over time, approaching 90% in the final year, reflecting operator experience and structured adoption of hybrid strategies. Lesion complexity (J-CTO ≥ 3) independently predicted technical failure, consistent with global data, while severely reduced LVEF also emerged as an independent determinant, suggesting that ventricular dysfunction may exert greater procedural impact in resource-constrained settings. Procedural safety was acceptable, with in-hospital MACCE within contemporary registry ranges and low twelve-month target lesion failure. Successful recanalization was strongly associated with improved mid-term outcomes and marked symptomatic relief, reinforcing the clinical value of CTO-PCI beyond angiographic endpoints. These findings support the feasibility and scalability of modern CTO programmes in similar healthcare environments and contribute meaningful prospective data from an underrepresented region.

Abbreviations

CTO: Chronic total occlusion

PCI: Percutaneous coronary intervention

CTO-PCI: Chronic total occlusion percutaneous coronary intervention

TIMI: Thrombolysis in Myocardial Infarction

MACCE: Major adverse cardiac and cerebrovascular events

TLF: Target lesion failure

LVEF: Left ventricular ejection fraction

CCS: Canadian Cardiovascular Society

NYHA: New York Heart Association

J-CTO: Japanese Chronic Total Occlusion score

IVUS: Intravascular ultrasound

ADR: Antegrade dissection and re-entry

AWE: Antegrade wire escalation

Declarations

Data availability

The data used in this study can be obtained from corresponding author, Ben Abdessalem Mohamed Aymen (m.aymen.benabdessalem@gmail.com) upon reasonable request.

Acknowledgements:

The authors thank the medical and nursing staff of the Cardiology Department of Farhat Hached University Hospital for their contribution to patient care.

Funding

This study was not supported by any sponsor or funder.

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Contributions

M.A.B.A. and J.B conceived the study, collected data, performed analysis, and drafted the manuscript. Z.B.A., H.F., M.Y., and A.M. contributed to data collection, interpretation, and manuscript revision. All authors read and approved the final manuscript.

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Funding:

No funding was provided during this observational prospective study.

Ethics statement :

This prospective observational study was approved by the Research Ethics Committee of Farhat Hached University Hospital and the Faculty of Medicine of Sousse. Written informed consent was obtained from all participants. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Consent for publication :

Not applicable.

Competing interests :

The authors declare no competing interests.

Disclosure of interest :

The authors report no conflicts of interest.

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Figures

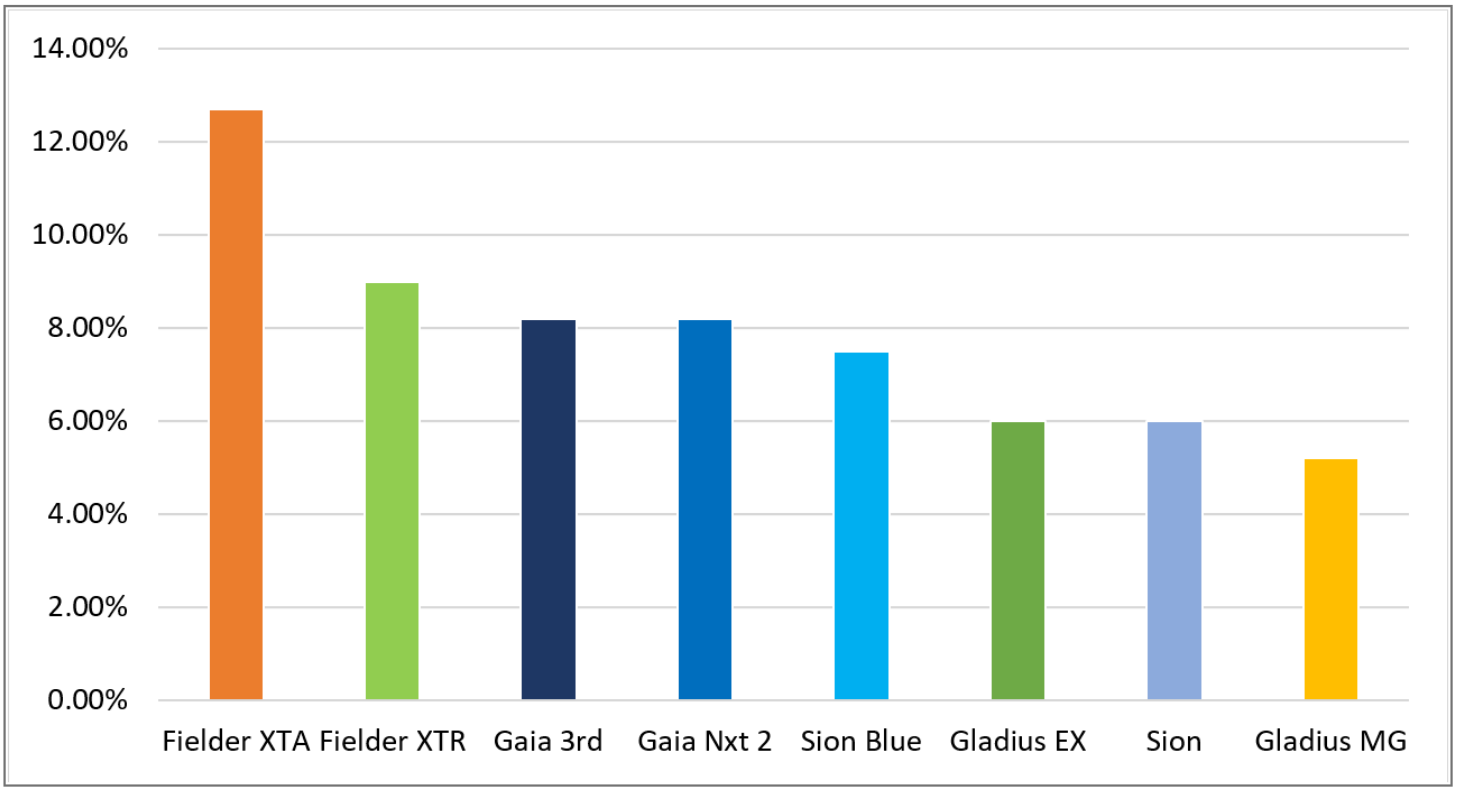


Figure 1

Distribution of Guidewires Used for Successful CTO Crossing

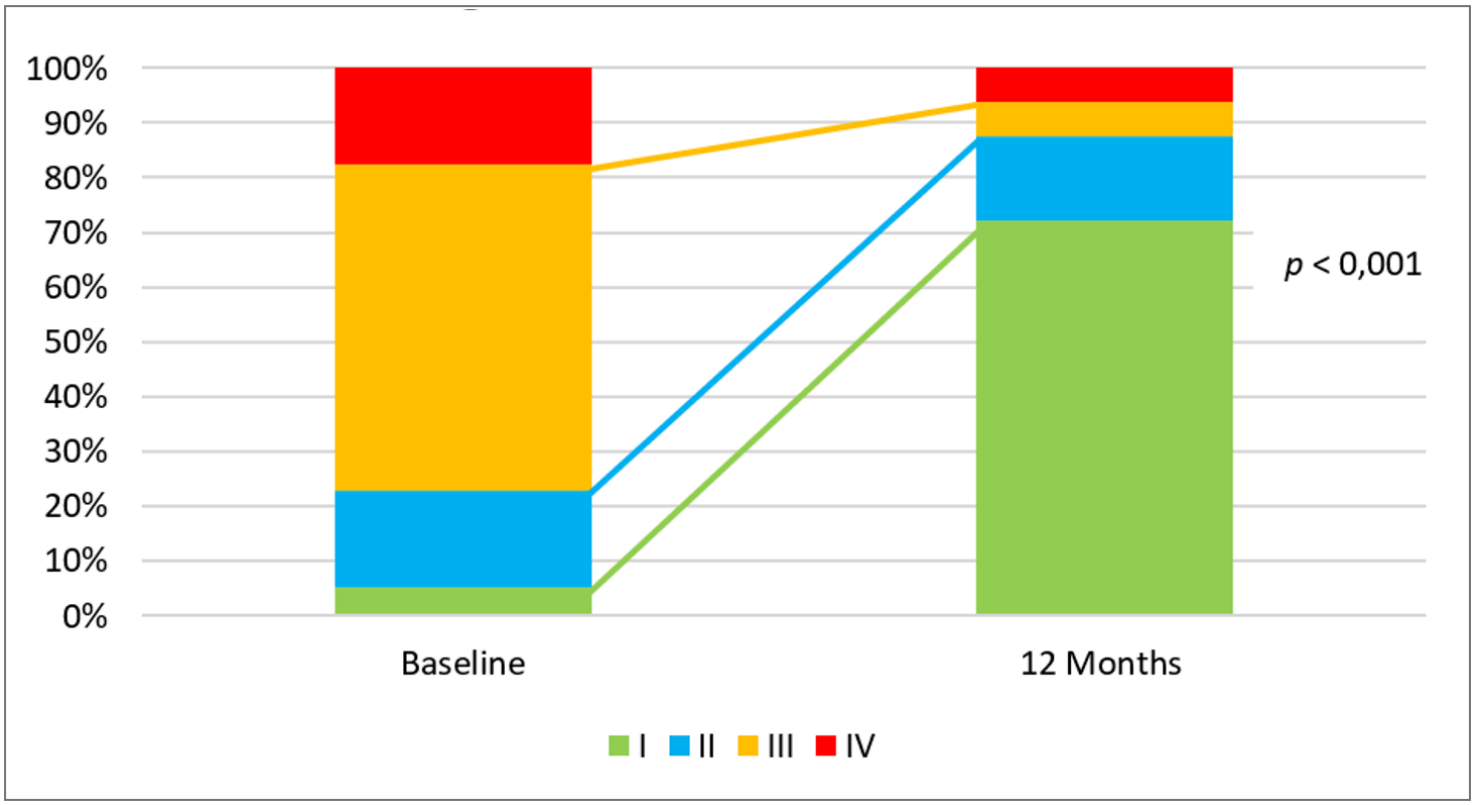


Figure 2

Change in CCS Class after CTO-PCI