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Incidence, Mechanisms, Treatment, and Outcomes of Coronary Artery Perforation During Chronic Total Occlusion Percutaneous Coronary Intervention

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Coronary artery perforation is a feared complication of chronic total occlusion (CTO) percutaneous coronary intervention (PCI). Our objective was to describe the incidence, mechanisms, treatment, and outcomes of coronary artery perforation during CTO PCI. We analyzed the baseline clinical and angiographic characteristics and procedural outcomes of 10,454 CTO PCIs performed in 10,219 patients between 2012 and 2022. The incidence of coronary perforation was 4.9% (n = 503). Patients who experienced coronary perforation were older and were more likely to have had previous coronary artery bypass graft surgery. Procedures that resulted in perforation were more complex, with higher Japanese CTO and Prospective Global Registry for the Study of Chronic Total Occlusion Intervention (PROGRESS-CTO) scores. Technical (66% vs 87%, p <0.001) and procedural (55% vs 87%, p <0.001) success rates were lower in perforation cases. The CTO target vessel was the most common perforation site (66%). The retrograde approach was responsible for the perforation in 47% of cases, and guidewire exit was the most common perforation mechanism. The proportion of Ellis class 1, 2, 3, and 3 -"cavity spilling" coronary perforations was 20%, 41%, 28%, and 11%, respectively. In 52% of perforations, 1 or more interventions were required: prolonged balloon inflation (23%), covered stent deployment (21%), coil embolization (6%), and/or autologous fat embolization (4%). Tamponade requiring pericardiocentesis occurred in 69 patients (14%). The incidence of major adverse cardiovascular events was higher in perforation cases (18% vs 1.3%, p <0.001). In conclusion, coronary artery perforation occurred in 4.9% of CTO PCIs performed by experienced operators and was associated with lower technical success and higher in-hospital major adverse cardiovascular events. **(Am J Cardiol 2022;00:1−8)**

Coronary artery perforation is one of the most feared complications of chronic total occlusion (CTO) percutaneous coronary intervention (PCI), as it can lead to significant adverse outcomes, such as pericardial effusion and tamponade.[1,2] The incidence of perforation is higher in CTO PCI (4% to 10%)[3−5] compared with PCI of non-CTO vessels likely due to higher lesion complexity (calcification, tortuosity, bifurcations), use of higher tip

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load guidewires, and advanced crossing techniques, such as antegrade dissection and re-entry and the retrograde approach.[6−8] We sought to describe the incidence, mechanisms, treatment, and outcomes of patients with coronary artery perforation in a large multicenter CTO PCI registry.

Methods

We analyzed the clinical and angiographic characteristics, and procedural outcomes of 10,454 CTO PCIs performed in 10,219 patients between 2012 and 2022 at 40 centers: United States (34), Canada (1), Europe (1), Turkey (2), Egypt (1), and the Russian Federation (1). Data collection was recorded in a dedicated online database (PROGRESS-CTO [Prospective Global Registry for the Study of Chronic Total Occlusion Intervention]; *Clinicaltrials.gov* identifier: NCT02061436). Study data were collected and managed using Research Electronic Data Capture tools hosted at the Minneapolis Heart Institute Foundation.[9,10] The study was approved by the institutional review board of each center.

Coronary CTOs were defined as coronary lesions with Thrombolysis in Myocardial Infarction (TIMI) grade 0 flow of at least 3 month duration. Technical success was defined as successful CTO revascularization with achievement of <30% residual diameter stenosis within the treated segment and restoration of TIMI grade 3 antegrade flow. Procedural success was defined as the achievement of technical success without any in-hospital major adverse cardiac events (MACEs). The Japanese CTO score was calculated as described by Morino et al,[11] the PROGRESS-CTO score as described by Christopoulos et al,[12] and the PROGRESS-CTO complications score as described by Danek et al.[13] Coronary perforation was reported by operators contributing to the registry and classified according to the Ellis classification by angiographic appearance.

Categorical variables were expressed as percentages and compared using Pearson's chi-square test. Continuous variables are presented as mean ± SD or as median (interquartile range) unless otherwise specified and were compared using the student's *t* test for normally distributed variables and the Wilcoxon rank sum test for non-parametric variables, as appropriate. Multivariable logistic regression was performed to identify baseline clinical, angiographic, and procedural variables associated with the incidence of coronary perforation. Variables associated with coronary perforation on univariable logistic regression with $p < 0.1$ were entered into the model. Temporal trends were tested for significance with linear contrast analysis (for continuous variables) and with the Cochran-Armitage test (for categorical variables). All statistical analyses were performed using JMP Statistical Software version 16.0 (SAS Institute, Cary, North Carolina). A $p < 0.05$ was considered to indicate statistical significance.

Results

During the study period, 10,454 CTO PCIs were performed at the study centers in 10,219 patients. The mean patient age was 64 ± 10 years, 81% were men, and 29%

Table 1
Clinical characteristics of the study population, classified according to the occurrence of a coronary perforation

Variable	Overall (n = 10,219)	Perforation (n = 503)	No perforation (n = 9,716)	*P* value
Age (years)	64 ± 10	68 ± 10	64 ± 10	<0.001
Men (%)	7,729 (81%)	366 (79%)	7,363 (81%)	0.209
BMI (kg/m^2)	30 ± 6	30 ±5	31 ± 6	0.009
Diabetes mellitus (%)	3,942 (43%)	167 (38%)	3,775 (43%)	0.053
Hypertension (%)	8,359 (90%)	429 (94%)	7,930 (89%)	<0.001
Current smokers (%)	2,361 (23%)	97 (19%)	2,264 (23%)	0.034
Left ventricular EF (%)	50 ± 13	50 ± 13	50 ± 13	0.954
Family history of CAD (%)	2,460 (32%)	122 (33%)	2338 (32%)	0.651
Congestive heart failure (%)	2,596 (29%)	142 (33%)	2,454 (29%)	0.076
Prior MI (%)	3,995 (45%)	221 (51%)	3774 (45%)	0.011
Prior PCI (%)	5911 (62%)	337 (71%)	5,574 (62%)	<0.001
Prior CABG (%)	2,792 (29%)	196 (41%)	2,596 (29%)	<0.001
Cerebrovascular disease (%)	926 (10%)	61 (14%)	865 (10%)	0.009
Peripheral arterial disease (%)	1,293 (14%)	96 (22%)	1197 (14%)	<0.001
CAD presentation				0.318
■ Stable angina pectoris (%)	6,030 (67%)	310 (72%)	5,720 (67%)	
■ Unstable angina pectoris (%)	1,327 (15%)	54 (13%)	1,273 (15%)	
■ NSTEMI (%)	701 (8%)	27 (6%)	674 (8%)	
■ STEMI (%)	121 (1%)	3 (1%)	118 (1%)	
■ Non-ischemic symptoms (%)	214 (2%)	10 (2%)	204 (2%)	
■ No symptoms (%)	565 (7%)	27 (6%)	538 (7%)	
Baseline creatinine (mg/dl)	1.0 (0.9,1.2)	1.1 (0.9,1.3)	1.0 (0.9,1.2)	0.084
Currently on dialysis (%)	223 (2.4%)	12 (2.7%)	211 (2.4%)	0.712

BMI = body mass index; CABG = coronary artery bypass graft; CAD = coronary artery disease; EF = ejection fraction; MI = myocardial infarction; NSTEMI = non-ST segment elevation myocardial infarction; PCI = percutaneous coronary intervention; STEMI = ST segment elevation myocardial infarction.

Table 2
Angiographic and procedural characteristics of the study patients, classified according to the occurrence of a coronary perforation

Variable	Overall (n = 10,454)	Perforation (n = 503)	No perforation (n = 9,951)	*P* value
Angiographic characteristics				
CTO target artery				0.046
■ Right coronary (%)	5,153 (53%)	288 (59%)	4,865 (53%)	
■ Left anterior descending (%)	2,545 (26%)	103 (21%)	2,442 (26%)	
■ Left circumflex (%)	1,843 (19%)	83 (17%)	1,760 (19%)	
■ Saphenous vein graft (%)	11 (0.1%)	0 (0%)	11 (0.1%)	
■ Left main (%)	48 (0.5%)	3 (0.6%)	45 (0.5%)	
■ Other (%)	145 (1.5%)	6 (1.4%)	139 (1.4%)	
Vessel diameter (mm)	3.0 (2.5, 3.0)	3.0 (2.5, 3.0)	3.0 (2.5, 3.0)	0.692
Proximal cap ambiguity (%)	3,045 (35%)	211 (51%)	2,834 (34%)	<0.001
Side branch at the proximal cap (%)	4,710 (55%)	270 (65%)	4,440 (54%)	<0.001
Blunt/no stump (%)	4,814 (47%)	308 (61%)	4506 (46%)	<0.001
Moderate/severe calcium (%)	4,342 (47%)	291 (61%)	4,051 (46%)	<0.001
Moderate/severe proximal tortuosity (%)	2,765 (30%)	174 (37%)	2,591 (29%)	<0.001
Distal cap at bifurcation (%)	2,882 (33%)	158 (38%)	2,724 (33%)	0.024
Adequate distal landing zone (%)	5,866 (67%)	221 (54%)	5,645 (68%)	<0.001
In-stent restenosis (%)	1,559 (17%)	69 (15%)	1,490 (17%)	0.424
Prior attempt to open CTO (%)	1,901 (19%)	113 (23%)	1,788 (19%)	0.034
Procedural characteristics				
Crossing strategies used				
■ AWE (%)	8,829 (86%)	394 (78%)	8,435 (87%)	<0.001
■ Retrograde (%)	3,237 (32%)	314 (62%)	2,923 (30%)	<0.001
■ ADR (%)	2,196 (22%)	178 (35%)	2,018 (21%)	<0.001
Initial crossing strategy				<0.001
■ AWE (%)	8,475 (83%)	355 (71%)	8,120 (84%)	
■ Retrograde (%)	1,311 (13%)	115 (23%)	1,196 (12%)	
■ ADR (%)	433 (4%)	33 (6%)	400 (4%)	
Final successful crossing strategy				<0.001
■ AWE (%)	5,638 (55%)	97 (19%)	5,541 (57%)	
■ Retrograde (%)	1,918 (19%)	166 (33%)	1,752 (18%)	
■ ADR (%)	1,273 (12%)	70 (14%)	1,203 (12%)	
■ None (%)	1,390 (14%)	170 (34%)	1,220 (13%)	
'Interventional' collaterals (%)	4,851 (57%)	270 (66%)	4,581 (57%)	<0.001
IVUS use (%)	3,900 (47%)	199 (52%)	3,701 (47%)	0.087
Number of stents used	2.3 ± 1.1	2.9 ± 1.4	2.3 ± 1.1	<0.001

ADR = antegrade dissection and re-entry; AWE = antegrade wire escalation; CTO = chronic total occlusion; IVUS = intravascular ultrasound; LIMA = left internal mammary artery.

had previous coronary artery bypass graft surgery (CABG). The baseline clinical characteristics in the perforation and non-perforation groups are listed in Table 1. Patients who experienced coronary perforation were older, had higher prevalence of hypertension and peripheral arterial disease, and were more likely to have had a previous myocardial infarction (MI), previous PCI, and previous CABG. Coronary artery disease presentation and the prevalence of diabetes mellitus and dyslipidemia were similar between the 2 groups.

The angiographic and procedural characteristics in the perforation and non-perforation groups are listed in Table 2. The right coronary artery was more frequently the target lesion in the perforation group (60% vs 53%, p = 0.046). Procedures that resulted in perforation were longer (29 [20 to 40] mm vs 25 [15 to 40] mm, p <0.001) and more likely to have unfavorable characteristics, such as proximal cap ambiguity, a side branch at the proximal cap, a blunt or stumpless proximal cap, and/or moderate to severe calcification. The J-CTO score (2.9 ± 1.2 vs 2.3 ± 1.3, p <0.001), PROGRESS-CTO score (1.5 ± 1.0 vs 1.3 ± 1.0, p <0.001), and PROGRESS-CTO complication score (3.7 ± 1.9 vs 2.7 ± 1.9, p <0.001) were higher in the perforation group.

CTO PCIs in the perforation group more often required the use of antegrade dissection and re-entry (35% vs 21%, p <0.001) and the retrograde (62% vs 30%, p <0.001) approach. While antegrade wiring was the most common successful crossing strategy in the non-perforation group (57% vs 19%, p <0.001), the retrograde approach (33% vs 18%, p <0.001) was the most frequent successful crossing strategy in cases with perforation. The proportion of lesions that were both balloon uncrossable and balloon undilatable was higher in the perforation group (16% vs 10%, p <0.001% and 18% vs 8%, p <0.001, respectively). Rotational atherectomy was used more frequently in cases with perforation (6.8% vs 3.3%, p <0.001).

Procedural outcomes are listed in Table 3. Overall technical and procedural success rates were 86% and 85%, respectively, and the incidence of in-hospital MACE was 2.1% (n = 215). Technical (66% vs 87%, p <0.001) and procedural (55% vs 87%, p <0.001) success rates were lower among perforation cases. Patients with perforation more frequently required the use of left ventricular assist

Table 3
Procedural outcomes of the study patients, classified according to the occurrence of a coronary perforation

Variable	Overall (n = 10,219)	Perforation (n = 503)	No perforation (n = 9,716)	*P* value
Procedure time (min)	114 (74, 168)	176 (122, 236)	112 (73, 164)	<0.001
Fluoroscopy time (min)	43 (26, 69)	74 (50, 98)	41 (25, 66)	<0.001
Patient AK dose (Gray)	2.2 (1.2, 3.7)	2.9 (1.7, 4.6)	2.1 (1.2, 3.6)	<0.001
Contrast volume (mL)	215 (150, 300)	250 (180, 380)	210 (150, 300)	<0.001
LVAD used (%)	353 (4%)	41 (10%)	312 (4%)	<0.001
▪ Prophylactic use (%)	261 (2.6%)	17 (3.4%)	244 (2.5%)	0.229
▪ Urgent use (%)	69 (0.7%)	25 (5%)	44 (0.5%)	<0.001
In-hospital MACE (%)	215 (2.1%)	91 (18%)	124 (1.3%)	<0.001
Death (%)	47 (0.5%)	20 (4%)	27 (0.3%)	<0.001
Acute MI (%)	66 (0.6%)	15 (3%)	51 (0.5%)	<0.001
Repeat-PCI (%)	24 (0.2%)	8 (1.6%)	16 (0.2%)	<0.001
Stroke (%)	18 (0.2%)	3 (0.6%)	15 (0.2%)	0.021
Emergency CABG (%)	10 (0.1%)	4 (0.8%)	6 (0.1%)	<0.001
Tamponade requiring pericardiocentesis (%)	98 (0.9%)	69 (14%)	29 (0.3%)	<0.001
Dissection/thrombus of donor artery (%)	71 (0.7%)	5 (1%)	66 (0.7%)	0.407
Vascular access site complication (%)	114 (1.1%)	12 (2.4%)	102 (1.1%)	0.005
Equipment loss (%)	39 (0.4%)	6 (1.2%)	33 (0.3%)	0.003

AK = air kerma; CABG = coronary artery bypass graft; LVAD = left ventricular assist device; MACE = major adverse cardiac events; MI = myocardial infarction; PCI = percutaneous coronary intervention.

devices (10% vs 3.8%, p <0.001) and had longer hospital stays after CTO PCI (2.7 ± 2.9 vs 1.4 ± 1.7 days, p <0.001).

The incidence of MACE was higher in perforation cases (18% vs 1.3%, p <0.001). Mortality among patients with perforation was 4% (n = 20), and the incidence of tamponade requiring pericardiocentesis was 14% (n = 69). Periprocedural MI, repeat PCI, emergency CABG surgery, and vascular access site complication were more frequent in perforation patients. Interventions in the perforation group required longer procedure and fluoroscopy time, higher air kerma radiation dose, and larger contrast volume.

On multivariable analysis, variables independently associated with the incidence of perforation were patient age, hypertension, peripheral arterial disease, proximal cap ambiguity, use of the retrograde approach, and use of antegrade dissection and re-entry (Figure 1).

Coronary artery perforation occurred in 503 patients (4.9%). The most common site of perforation was the CTO target vessel (66%), followed by septal (15%) and epicardial (12%) collaterals (Figure 2). The perforation occurred during retrograde crossing attempts in 47%, during antegrade wiring in 37%, and during antegrade dissection and re-entry in 16% of cases (Figure 2). Epicardial collaterals were used for retrograde crossing in 26% of the retrograde

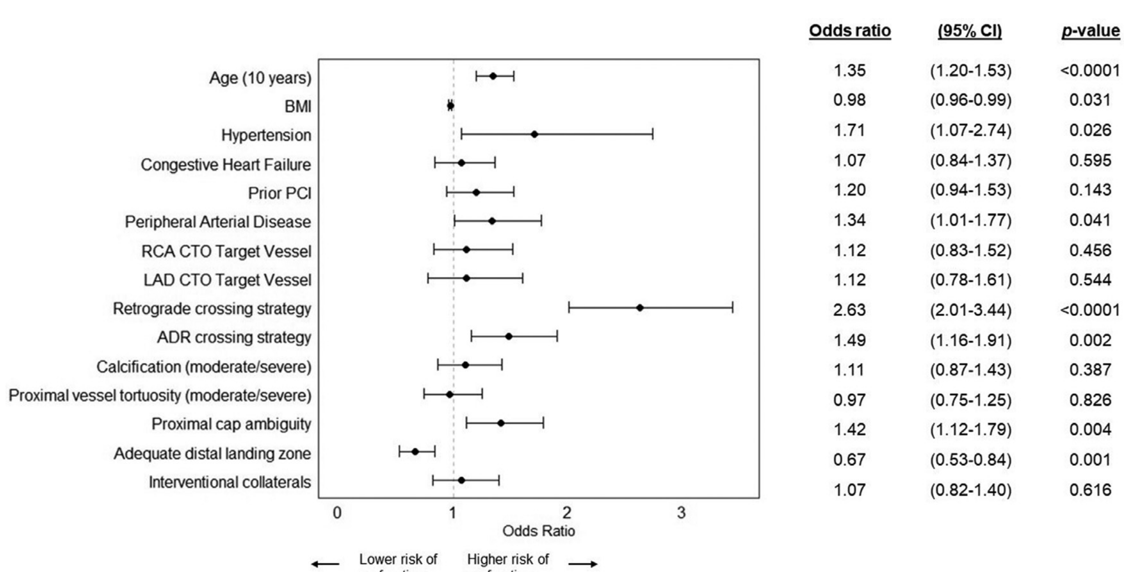

Figure 1. Forest plot showing odds ratios for variables associated with the incidence of coronary perforation. ADR = anterograde dissection and re-entry; BMI = body mass index; LAD = left anterior descending artery; PCI = percutaneous coronary intervention; RCA = right coronary artery.

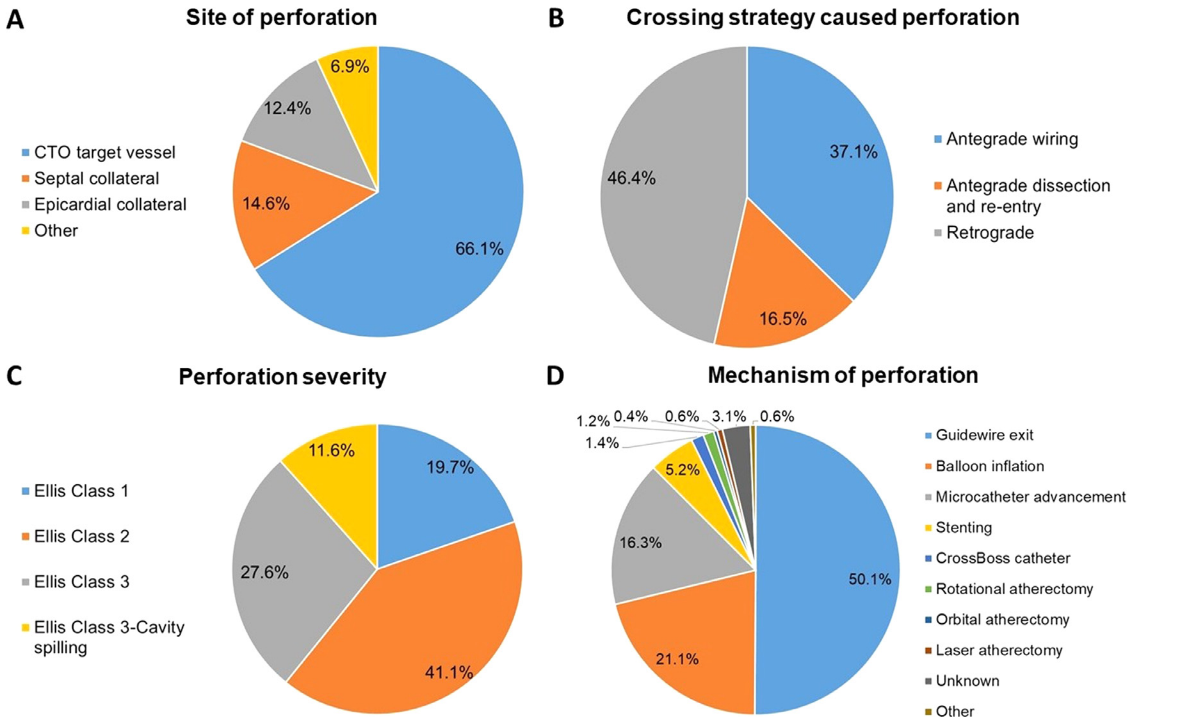

Figure 2. Pie charts for *(A)* Site of perforation; *(B)* Crossing strategy caused perforation; *(C)* Perforation severity; *(D)* Mechanism of perforation.

cases overall, resulting in a perforation in 7% of the attempts. Septal collaterals were used in 64% of the retrograde cases, resulting in a perforation in 3% of the attempts. The proportion of Ellis class 1, 2, 3, and 3—"cavity spilling" coronary perforations was 20%, 41%, 28%, and 11%, respectively (Figure 2).

The mechanisms of perforation are shown in Figure 2. The most common mechanism of perforation was guidewire exit (50%). In 21% of cases, perforation was caused by balloon inflation, whereas in 16% of cases, it was caused by microcatheter advancement. Stent induced perforations were observed in 5% of cases, and intravascular ultrasound was used for sizing in 64% of cases.

The management of the cases that resulted in perforation is listed in Table 4. In 137 of 503 cases (27%), no treatment was necessary for the perforation, 103 of 503 (21%) of the cases required anticoagulation reversal, and 52% of the cases required 1 or more interventions to treat the perforation. As shown in Figure 3, use of covered stents for perforation treatment increased over time, from 11% (4 of 38) in 2016 to 32% (24 of 75) in 2021 (p for trend <0.001), as did the use of coil embolization, from 3% (1 of 38) in 2016 to 12% (9 of 75) in 2021 (p for trend = 0.015).

The management of perforations stratified by the Ellis class is illustrated in Figure 4. Although observation and anticoagulation reversal were the most common management strategies for Ellis class 1 and 2 perforations, covered stent (46%) and prolonged balloon inflation (44%) were the most commonly used approaches for Ellis class 3 perforation. Ellis class 3-"cavity spilling" perforations required no treatment in 48%; however, in 28% of the cases, a covered stent was implanted to seal the perforation. Pericardiocentesis was required in 14% and 24% of Ellis class 2 and 3 perforations, respectively.

Table 4
Management of cases that resulted to perforation

	n = 503
No treatment necessary (%)	137 (27%)
Anticoagulation reversal (%)	103 (21%)
Prolonged balloon inflation (%)	115 (23%)
Covered stent (%)	106 (21%)
Coil embolization (%)	30 (6%)
Fat embolization (%)	18 (4%)
Pericardiocentesis (%)	69 (14%)
Emergency surgery (%)	4 (1%)
Other (%)	24 (5%)

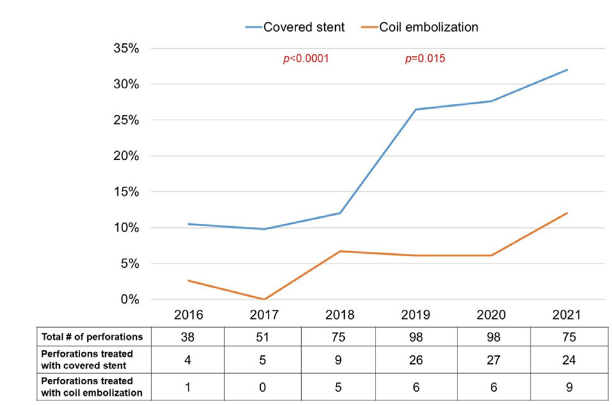

Figure 3. Temporal trends in the treatment of perforation with covered stent and coil embolization.

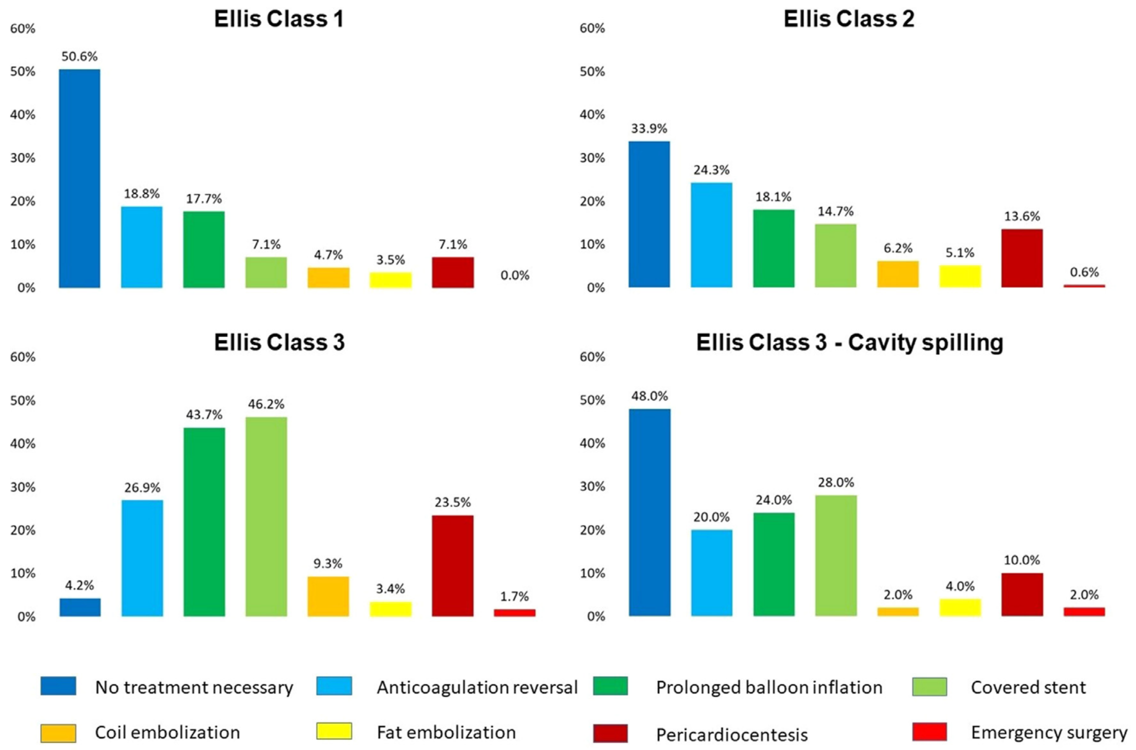

Figure 4. Coronary perforation treatment stratified by Ellis class.

Discussion

The main findings of our study are as follows: (1) the incidence of coronary artery perforation in a large registry of experienced centers was 4.9%; (2) age, hypertension, peripheral arterial disease, proximal cap ambiguity, and use of advanced CTO crossing techniques were independently associated with perforation; (3) technical and procedural success rates were lower, and the incidence of MACE was higher in perforation cases; (4) half of the perforation cases were due to injury to the CTO target vessel, and almost 50% were related to use of the retrograde approach; (5) guidewire exit was the most common perforation mechanism; (6) more than half of perforations cases required 1 or more interventions, with prolonged balloon inflation and covered stenting being most frequent; (7) in perforation cases, the mortality rate was 4%, and the incidence of tamponade requiring pericardiocentesis was 14%.

Azzalini et al[14] analyzed data from 1,811 consecutive patients who underwent CTO PCI at 5 centers between 2011 and 2018 and reported the epidemiology, mechanisms, management, and outcomes of coronary perforation during CTO PCI. Perforation occurred in 99 patients (5.5%), an incidence similar to our study (4.9%). Similar to our study, approximately half of perforations were due to injury in the CTO vessel, guidewire exit was the most common mechanism of perforation, and 53% of the cases required intervention, with covered stent being the treatment strategy in 25% of the cases. One-fifth of patients with perforation required pericardiocentesis, and 5% died, which are slightly higher rates than those found in our analysis (14% and 4%, respectively). Furthermore, similar to our study, they reported that age and the use of more advanced techniques, such as antegrade dissection and reentry and retrograde approach, were independently associated with perforation.

In 2019, a study of 1,000 consecutive patients from the OPEN-CTO (Outcomes, Patient health status, and Efficiency in Chronic Total Occlusion hybrid procedures) registry reported 89 cases (9%) of perforation, with 43 (48%) of those being clinically significant requiring treatment.[15] When the mechanism of perforations was assessed by the core laboratory, 45% of the perforations occurred during retrograde crossing, findings comparable with those seen in our study (47%). In-hospital death occurred in 9 (10%) of the perforation cases, and 10 cases (11%) were complicated by tamponade. Hirai et al[15] reported that larger size, proximal or collateral location, and high-risk shapes of a coronary perforation were associated with major adverse events.

Kinnaird et al[16] analyzed data from 26,807 CTO PCIs from the British Cardiovascular Intervention Society data set between 2006 and 2013 and reported an incidence of perforation of 1.4%, with an increasing trend during the study period. The main predictors of perforation were age, female gender, and lesion complexity. They identified a significant impact not only on early morbidity and mortality in perforation cases, but also a longer-term legacy effect on 12-month mortality. In contrast, Wu et al[17] reported that perforation during retrograde CTO PCI through epicardial collaterals was not significantly associated with adverse long-term clinical outcomes. Possible explanations for the similar long-term outcomes in patients with perforations are the evolving techniques over the years, and prompt management of perforation by skilled operators.

Although in some perforation cases, no specific management may be needed apart from careful observation, severe perforations require emergent treatment. Immediate prolonged balloon inflation is often crucial to prevent accelerated accumulation of blood in the pericardial space and tamponade.[18,19] Large vessel perforations are usually treated with covered stents.[20] Treatment options for distal vessel perforations include coil embolization,[21,22] autologous fat embolization,[23] or thrombin injection.[24] In cases of pericardial effusion and tamponade, emergency pericardiocentesis or CABG should be promptly performed.[1,19]

Prevention is critical to decreasing the incidence of perforation during CTO PCI. Some preventive strategies are: (1) confirming guidewire position within the main vessel in multiple angiographic projections before balloon dilation and/or microcatheter advancement, usually through injection of the donor vessel to opacity the distal portion of the CTO vessel; (2) use of intravascular imaging to clarify the vessel size, lesion preparation, and guide balloon and stent size; (3) outlining the anatomy of the collateral channel before and during crossing.[19]

This study has limitations. First, PROGRESS-CTO is an observational retrospective study without long-term follow-up for all patients. Second, there was no core laboratory assessment of the study angiograms or clinical event adjudication. Third, the procedures were performed at dedicated, high-volume CTO centers by skilled and experienced operators, limiting the generalizability of our findings to centers with limited CTO PCI experience.

In conclusion, coronary artery perforations were observed relatively infrequently in CTO PCI performed by skilled and experienced operators in high-volume CTO centers around the world and are associated with lower technical success and higher in-hospital MACE. Patient age, hypertension, peripheral arterial disease, proximal cap ambiguity, and use of advanced CTO crossing techniques were associated independently with the development of perforation.

Disclosures

Dr. Alaswad: Consultant and speaker for Boston Scientific, Abbott Cardiovascular, Teleflex, and Cardiovascular Systems, Inc. Dr. Karmpaliotis: Honoraria - Boston Scientific and Abbot Vascular; Equity: Saranas, Soundbite, Traverse Vascular. Dr. Jaffer: Sponsored research: Canon, Siemens, Shockwave, Teleflex, Mercator, and Boston Scientific; Consultant: Boston Scientific, Siemens, Magenta Medical, International Medical Device Solutions, Asahi Intecc, Biotronik, Philips, Intravascular Imaging Inc. Equity interest: Intravascular Imaging Inc, DurVena. Massachusetts General Hospital - licensing arrangements: Terumo, Canon, and Spectrawave, for which Dr. Jaffer has the right to receive royalties. Dr. Khatri: Personal Honoria for proctoring and speaking: Abbott Vascular, Asahi Intecc Co., Ltd., Terumo, and Boston Scientific. Dr. Poommipanit: Asahi Intecc Co., Ltd., Abbott, Vascular-Consultant. Dr. Jaber: Medtronic and proctoring fees from Abbott. Dr. Rinfret: Abbott Vascular, Abiomed, Boston Scientific Corporation, SoundBite Medical, Teleflex consultant. Dr. Nicholson: Is a proctor and on the speakers' bureau and the advisory board for Abbott Vascular, Boston Scientific, and Asahi Intecc Co., Ltd.; he reports intellectual property with Vascular Solutions. Dr. Patel: Consulting Honoraria from Abbott, Medtronic, Terumo, and Cardiovascular Systems, Inc. Dr. Mahmud: Consultant for Abiomed, Medtronic, and Boston Scientific, and chairs multiple Data, Safety, and Monitoring Boards. Dr. Davies: Honoraria from Asahi Intecc Co., Ltd., Boston Scientific, Medtronic, and Siemens Healthineers, in addition to being a member of an advisory board for Shockwave Medical. Dr. Kerrigan: Consultant to Abiomed, Asahi Intecc Co., Ltd., Biotronik, Cordis, Boston Scientific, Ischemaview Inc., Osprey Medical, Penumbra, Philips, and Teleflex. Dr. Abi-Rafeh: Proctor and speaker honoraria for Boston Scientific and Abbott Vascular. Dr. ElGuindy: Consulting honoraria: Medtronic, Boston Scientific, Asahi Intecc Co., Ltd., Abbott; Proctorship fees: Medtronic, Boston Scientific, Asahi Intecc Co., Ltd., and Terumo; Educational grants: Medtronic. Dr. Brilakis: Consulting/speaker honoraria from Abbott Vascular, American Heart Association (Associate Editor: Circulation), Amgen, Asahi Intecc Co., Ltd., Biotronik, Boston Scientific, Cardiovascular Innovations Foundation (Board of Directors), ControlRad, CSI, Elsevier, GE Healthcare, IMDS, InfraRedx, Medicure, Medtronic, Opsens, Siemens, and Teleflex; Research support: Boston Scientific, GE Healthcare; owner at Hippocrates LLC; shareholder at Minneapolis Heart Institute Ventures, Cleerly Health, and Stallion Medical. The remaining authors have no conflicts of interest to declare.

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