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STATE-OF-THE-ART REVIEW

Update in the Percutaneous Management of Coronary Chronic Total Occlusions

Peter Tajti, MD,[a,b] M. Nicholas Burke, MD,[a] Dimitri Karmpaliotis, MD, PhD,[c] Khaldoon Alaswad, MD,[d] Gerald S. Werner, MD,[e] Lorenzo Azzalini, MD, PhD, MSc,[f] Mauro Carlino, MD,[f] Mitul Patel, MD,[g] Kambis Mashayekhi, MD,[h] Mohaned Egred, MD,[i] Oleg Krestyaninov, MD,[j] Dmitrii Khelimskii, MD,[j] William J. Nicholson, MD,[k] Imre Ungi, MD, PhD,[b] Alfredo R. Galassi, MD,[l] Subhash Banerjee, MD,[m] Emmanouil S. Brilakis, MD, PhD[a,m]

ABSTRACT

Percutaneous coronary intervention (PCI) for chronic total occlusions (CTOs) has been rapidly evolving during recent years. With improvement in equipment and techniques, high success rates can be achieved at experienced centers, although overall success rates remain low. Prospective, randomized-controlled data regarding optimal use and indications for CTO PCI remain limited. CTO PCI should be performed when the anticipated benefit exceeds the potential risk. New high-quality studies of the clinical outcomes and techniques of CTO PCI are needed, as is the expansion of expert centers and operators that can achieve excellent clinical outcomes in this challenging patient and lesion subgroup. In the current review the authors summarize the latest publications in CTO PCI and provide an overview of the current state of the field. (J Am Coll Cardiol Intv 2018;11:615–25) © 2018 the American College of Cardiology Foundation. Published by Elsevier. All rights reserved.

From the [a]Minneapolis Heart Institute, Abbott Northwestern Hospital, Minneapolis, Minnesota; [b]Division of Invasive Cardiology, University of Szeged, Second Department of Internal Medicine and Cardiology Center, Szeged, Hungary; [c]Department of Cardiology, Columbia University, New York, New York; [d]Department of Cardiology, Henry Ford Hospital, Detroit, Michigan; [e]Medizinische Klinik I (Cardiology and Intensive Care), Klinikum Darmstadt GmbH, Darmstadt, Germany; [f]Division of Interventional Cardiology, Cardio-Thoracic-Vascular Department, San Raffaele Scientific Institute, Milan, Italy; [g]Department of Cardiology, UC San Diego Sulpizio Cardiovascular Center and VA San Diego Healthcare System, La Jolla, California; [h]Division of Cardiology and Angiology II, University Heart Center Freiburg Bad Krozingen, Bad Krozingen, Germany; [i]Department of Cardiology, Freeman Hospital, Newcastle upon Tyne, United Kingdom; [j]Meshalkin Siberian Federal Biomedical Research Center, Ministry of Health of Russian Federation, Novosibirsk, Russian Federation; [k]Department of Cardiology, WellSpan York Hospital, York, Pennsylvania; [l]Department of Medical Sciences and Pediatrics, Catheterization Laboratory and Cardiovascular Interventional Unit, Cannizzaro Hospital, University of Catania, Catania, Italy; and the [m]VA North Texas Health Care System and University of Texas Southwestern Medical Center, Dallas, Texas. Dr. Burke has received consulting and speaker honoraria from Abbott Vascular and Boston Scientific. Dr. Karmpaliotis has received speaker honoraria from Abbott Vascular, Medtronic, Boston Scientific, and Vascular Solutions. Dr. Alaswad has served as a consultant for Terumo, Boston Scientific, Abbott Cardiovascular, Asahi Intecc, and Abbott Laboratories; and has served as a speaker for Boston Scientific. Dr. Werner has received speaker honoraria for Asahi Intecc, Abbott Vascular, Biosensors, and Terumo; and has served as the principal investigator of a randomized trial on the benefit of CTO PCI versus medical therapy conducted by the EURO CTO Club, sponsored by Asahi Intecc and Biosensors. Dr. Azzalini has received honoraria from Guerbet; and research support from ACIST Medical Systems. Dr. Patel has received consulting honoraria from Abbott Vascular. Dr. Mashayekhi has received honoraria from Asahi Intecc. Dr. Egred has served as a proctor for Boston Scientific (Vascular Perspective for CTO); and has received honoraria from Boston Scientific and Abbott Vascular. Dr. Nicholson has served as a proctor for Abbott Vascular, Boston Scientific, and Asahi Intecc; has served on the advisory board for Abbott Vascular, Boston Scientific, and Medtronic; and owns intellectual property in Vascular Solutions. Dr. Banerjee has received research grant support from Gilead and The Medicines Company; has received consultant/speaker honoraria from Covidien, Gore, AstraZeneca, Cardiovascular Systems, Inc., Janssen, and Medtronic; has received institutional research grant support from Boston Scientific and Merck; and owns equity in MDCARE Global (spouse) and intellectual property in HygeiaTel. Dr. Brilakis has received consulting/speaker honoraria from Abbott Vascular, ACIST Medical Systems, Amgen, Asahi Intecc, Cardiovascular Systems, Inc., Elsevier, GE Healthcare, Medicure Medtronic, and Nitiloop; has received research support from Boston Scientific and Osprey; and has a spouse who is an employee of Medtronic. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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ABBREVIATIONS AND ACRONYMS

CABG = coronary artery bypass grafting

CTA = computed tomography angiography

CTO = chronic total occlusion

IVUS = intravascular ultrasound

MACE = major adverse cardiac event(s)

MT = medical therapy

OMT = optimal medical therapy

PCI = percutaneous coronary intervention

Chronic total occlusion (CTO) percutaneous coronary intervention (PCI) is a rapidly evolving area of interventional cardiology. We sought to provide an update on current concepts in CTO PCI and a critical review of the recently published data.

CTOs: INCIDENCE AND EPIDEMIOLOGY

CTOs are found in 16% to 52% of patients who undergo coronary angiography and are found to have coronary artery disease (1–3). In the SCAAR (Swedish Coronary Angiography and Angioplasty Registry) registry, the prevalence of CTO among patients with at least one 50% luminal coronary stenosis was 16.1% (14,441 of 89,872 patients) (4). In a Canadian single-center registry the prevalence of a CTO was 20%: PCI was performed in 9% of these patients, 34% had coronary artery bypass grafting (CABG), and 57% were treated with medical therapy alone (5).

WHEN SHOULD CTO PCI BE PERFORMED?

CTO PCI should be performed when the anticipated benefits (which depend on the patient's baseline clinical condition and the likelihood of success) exceed the potential short- and long-term risks (**Central Illustration**) (6).

CTO PCI BENEFITS: RANDOMIZED STUDIES. Currently, symptom improvement is considered the main benefit of CTO PCI, despite criticisms that there is limited supportive prospective randomized-controlled clinical trial data: indeed, only 3 randomized-controlled trials have been reported to date, only 1 of which has been published (7).

The EXPLORE (Evaluating Xience and Left Ventricular Function in Percutaneous Coronary Intervention on Occlusions After ST-Elevation Myocardial Infarction) trial enrolled 304 patients who underwent primary PCI for acute ST-segment elevation acute myocardial infarction and had a coexisting non-infarct-related artery CTO. Patients were randomized to CTO PCI versus medical therapy alone. CTO PCI success was 73%. Cardiac magnetic resonance imaging performed after 4 months showed similar left ventricular ejection fraction and left ventricular end-diastolic volume in the 2 study groups (7).

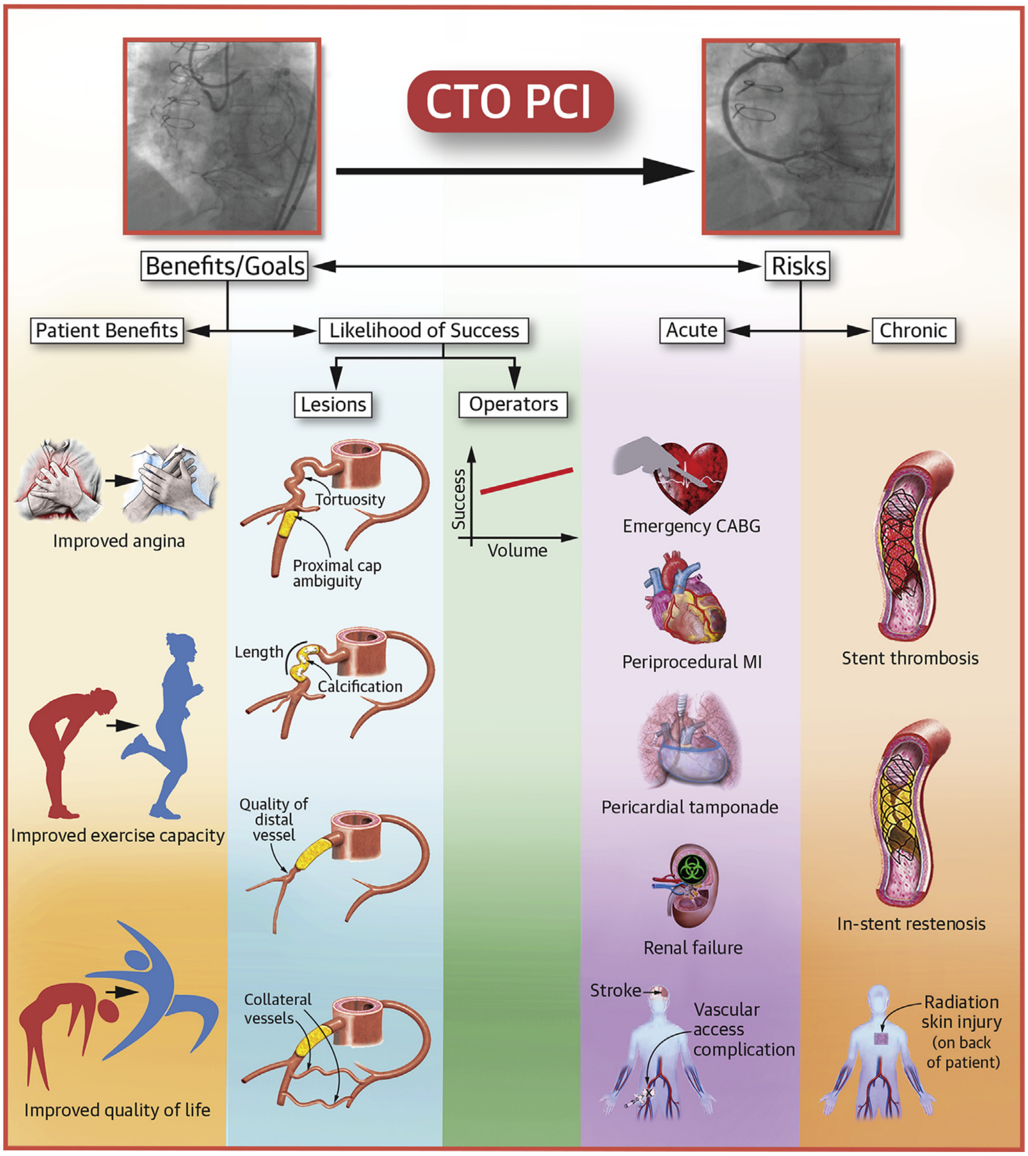
The DECISION-CTO (Drug-Eluting stent Implantation versus optimal Medical Treatment in patients with ChronIc Total OccluSION) trial (NCT01078051) was presented at the 2017 American College of Cardiology meeting. The DECISION-CTO trial randomized 834 patients with coronary CTOs (many of whom also had multivessel disease) to optimal medical therapy (OMT) alone versus OMT + CTO PCI. Patients in the OMT and the OMT + CTO PCI group had similar clinical outcomes during a median follow-up of 3.1 years. The study has several limitations, such as suboptimal primary endpoint selection, high rate of non-CTO PCI (73% of the study patients had multivessel disease in both groups), early termination before achievement of target enrollment, high crossover rates (18% in the OMT alone group underwent CTO PCI), and mild baseline symptoms in both study groups.

The EuroCTO (A Randomized Multicentre Trial to Evaluate the Utilization of Revascularization or Optimal Medical Therapy for the Treatment of Chronic Total Coronary Occlusions) trial (NCT01760083) was presented at the 2017 EuroPCR meeting. Due to slow enrollment, the study ended prematurely after randomizing 407 patients instead of the planned 1,200. In contrast to DECISION-CTO trial, non-CTO lesions were treated before enrollment in the study. Compared with patients randomized to medical therapy only, patients randomized to CTO PCI had more improvement in angina frequency at 12 months ($p = 0.009$) as assessed by the Seattle Angina Questionnaire.

CTO PCI BENEFITS: OBSERVATIONAL STUDIES. Several observational, uncontrolled studies have suggested clinical benefit with CTO PCI, by improving angina, dyspnea, depression, exercise capacity, and risk for arrhythmias.

Despite the limitation of comparing successful with failed CTO PCIs, the OPEN-CTO (Outcomes, Patient Health Status, and Efficiency in Chronic Total Occlusion Hybrid Procedures) registry analyzed 1,000 consecutive patients undergoing CTO PCI with the hybrid approach (**Figure 1**) using standardized questionnaires. A 10.8-point (95% confidence interval: 6.3 to 15.3) improvement in the quality-of-life domain of the Seattle Angina Questionnaire was observed among successful versus unsuccessful procedures ($p < 0.001$) (8). Similar results have been shown in multiple prior studies and meta-analyses (9), which have also reported lower mortality among successful versus failed CTO PCIs (9). Several studies have assessed the long-term outcomes of CTO PCI as compared with medical therapy, reporting lower incidence of major adverse cardiac events with CTO PCI (10,11), even among patients with well-developed collateral circulation (12). However, all retrospective studies are subject to selection bias.

CENTRAL ILLUSTRATION Overview of the Potential Risks and Benefits of CTO PCI



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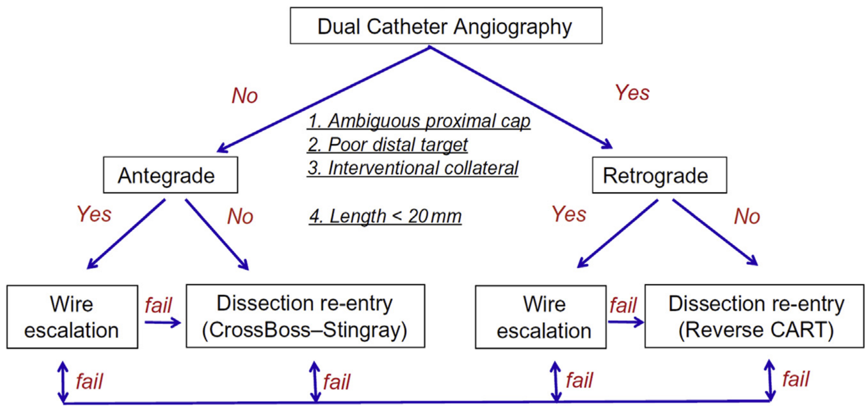
Parameters that can help determine the risks and benefits of chronic total occlusion percutaneous coronary intervention. CABG = coronary artery bypass grafting; CTO = chronic total occlusion; MI = myocardial infarction; PCI = percutaneous coronary intervention.

Patients with CTOs often have depression that improves after successful CTO PCI (13). CTO PCI also increases exercise capacity with longer 6-min walking distance (417 ± 126 m vs. 463 ± 103 m; $p = 0.002$) in one study, likely due to lower angina frequency (39% vs. 8%; $p < 0.001$) and less ischemia, especially in patients with larger baseline ischemic burden (14). Two studies performed cardiopulmonary testing before and after CTO PCI, showing increased peak oxygen consumption and anaerobic threshold (15,16). CTOs may be associated with higher arrhythmic risk: patients with prior myocardial infarction and a CTO had greater area of scar tissue (34 cm^2 vs. 19 cm^2; $p = 0.001$) and higher frequency of recurrent ventricular tachycardia after ablation during a median follow up of 19 months (47% vs. 16%; $p = 0.003$) (17).

FIGURE 1 Hybrid Algorithm for CTO PCI



Dual angiography is performed and 4 parameters are assessed: proximal cap ambiguity, lesion length, quality of the distal vessel, and presence of interventional collaterals. Based on these 4 parameters the initial crossing strategy is selected, followed by early change in case of failure to achieve progress with any selected strategy. CART = controlled antegrade and retrograde subintimal tracking. Reproduced with permission from Brilakis (6).

Several studies have shown that subsequent outcomes are significantly better after successful than after failed CTO PCI (9), but such analyses have multiple inherent limitations. Several other retrospective studies have compared the outcomes of CTO PCI with medical therapy. In an Italian multicenter registry of 1,777 patients with CTOs treatment was as follows: PCI (43.7%), medical therapy (MT) (46.5%), or surgery (9.8%). At 1-year follow-up, cardiac death (1.4% vs. 4.7% and 6.3%; $p < 0.001$) and major adverse cardiac events (MACE) (2.6% vs. 8.2% and 6.9%; $p < 0.001$) were significantly lower in the PCI group than in MT or CABG groups (10). In propensity-matched analysis MT was associated with higher MACE rate, death, and rehospitalization (10). Similar results were observed in patients with well-developed collateral circulation (12).

In summary, CTO PCI improves patient symptoms, whereas there is limited, retrospective data on whether it can affect the subsequent incidence of death, myocardial infarction, and arrhythmias. Accordingly, the primary indication for offering and performing CTO PCI should be the alleviation of symptoms.

CTO PCI SUCCESS RATES. Achieving clinical benefit with CTO PCI requires the procedure to be successful. With contemporary equipment and techniques (e.g., the hybrid algorithm) (**Figure 1**) (18), high success rates (85% to 90%) are achieved at experienced centers (**Table 1**) (19–24). However, success rates in unselected populations remain low: 61.3% in the New York State PCI Registry (25) and 59% in the U.S. National Cardiovascular Data Registry (vs. 96% in nonocclusive lesions; $p < 0.001$) (26). Therefore, there is a gap between what is achieved at dedicated CTO PCI centers and the outcomes at less experienced centers. Bridging this gap remains a challenge and should be a major focus of current research and education efforts.

TABLE 1 Procedural Outcomes From Multicenter CTO Registries Published in Recent Years

First Author (Ref. #)	Study Period	Centers	Cases	Technical Success	Procedural Success	Overall MACE	Death	Acute MI	Stroke	TVR	Pericardial Tamponade
Christopoulos et al. (19)	2012–2015	11	1,036	91%	90%	1.7%	0.3%	0.7%	0.1%	0.2%	0.5%
Habara et al. (23)	2012–2013	56	3,229	–	88%	0.5%	0.2%	0.1%	0.1%	–	0.3%
Wilson et al. (20)	2012–2014	7	1,156	90%	–	1.6%	0.0%	0.8%	0.4%	0.0%	0.7%
Maeremans et al. (24)	2014–2015	17	1,253	89%	86%	2.6%	0.2%	0.2%	2.2%	0.1%	1.3%
Sapontis et al. (8)	2013–2017	12	1,000	86%	85%	7.0%	0.9%	2.6%	0.0%	0.1%	–*

*The tamponade rate was not reported. The rate of clinical perforation was 4.8%.

CTO = chronic total occlusion; MACE = major adverse cardiovascular events; MI = myocardial infraction; TVR = target vessel revascularization.

TABLE 2 Summary of Available Scoring Systems for Procedural Planning in CTO PCI

	J-CTO Score (27)	PROGRESS-CTO Score (31)	RECHARGE Score (32)	CL Score (33)	ORA Score (34)	Ellis Score (35)	PROGRESS Complications Score (37)
Stump morphology	Blunt stump (1)	Ambiguous proximal cap (1)	Blunt stump (1)	Blunt stump (1.0)	–	Ambiguous proximal cap (1)	–
Length	>20 mm (1)	–	>20 mm (1)	>20 mm (1.5)	–	>10 mm (1)	≥23 mm (2)
Ostial location					Ostial location (1)	Ostial location (1)	
Target vessel	–	Circumflex target vessel (1)	Bypassed CTO target vessel (1)	Non-LAD (1.0)	–	–	–
Tortuosity	Intralesion bending ≥45° (1)	Moderate/severe proximal tortuosity (1)	Intralesion bending ≥45° (1)	–	–	Retrograde tortuosity (1)	–
Calcification	Mild to moderate (1)	–	Visible calcification (1)	Severe (2.0)	–	Moderate to severe (1)*	–
Procedural characteristics	Previously failed CTO attempt (1)	–	–	–	–	Operator variable (1)	Retrograde approach used (1)
Distal target/collateral vessels	–	Lack of interventional collateral vessels (1)	Diseased distal target vessel (1)	–	Rentrop 1-2 filling (2)	Poor distal target (1), collateral score (2)†	–
Clinical characteristics	–	–	–	Previous CABG (1.0) or MI (1.0)	–	–	–
Age, yrs	–	–	–	–	≥75 (1)	–	≥65 (3)
Prediction	Wire crossing in 30 min (0) 92.3% (1) 58.3% (2) 34.8% (≥3) 22.2%	Technical success (0) 98.2% (1) 97.5% (2) 91.6% (≥3) 76.7%	Technical success (0-1) 98% (2) 90% (3) 73% (4) 69% (5) 44% (6) 14%	Technical success (0.0-1.0) 88.3% (1.5-2.5) 73.1% (3.0-4.5) 59.4% (≥5.0) 46.2%	Technical success (0) 96.8% (1) 96.4% (2) 71.9% (≥3) 58.8%	Technical success (0) 100% (1) 89.1% (2) 70.2% (3) 61.9% (4) 0% (4-5) 75%*	Risk of MACE (0-2) 0.2% (3-4) 2.0% (≥5) 6.6%

*Moderate-to-severe calcification is considered as part of the extended Ellis score. †Using specific collateral classification scoring (range 0-2) combining Werner collateral classification (82), collateral type (septal, epicardial, other), and tortuosity. Each number in parentheses reflects the points added if the lesion has this parameter.

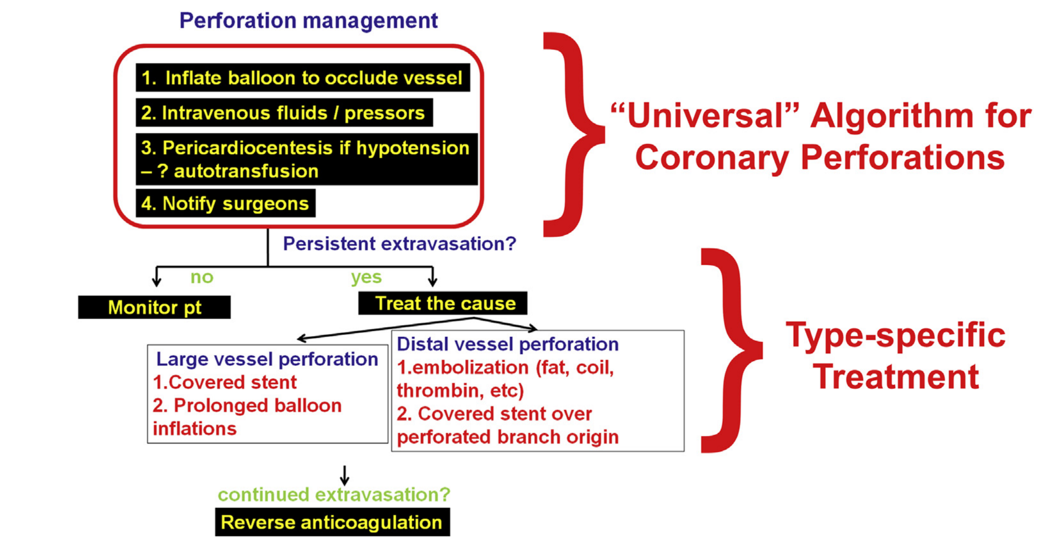
CABG = coronary artery bypass grafting; CL score = clinical and lesion related score; CTO = chronic total occlusion; J-CTO = Multicenter CTO Registry of Japan; LAD = left anterior descending artery; MI = myocardial infarction; ORA = ostial location, collateral filling of Rentrop <2, age over 75; PCI = percutaneous coronary intervention; PROGRESS = PROspective Global REgiStry for the Study of Chronic Total Occlusion Intervention; RECHARGE = REgistry of Crossboss and Hybrid Procedures in FrAnce, the NetheRlands, BelGium and UnitEd Kingdom.

Patient-specific estimation of the likelihood of success can be facilitated by using various scoring systems (**Table 2**). The first CTO PCI score was the J-CTO (Multicenter CTO Registry of Japan) score that was developed to estimate the likelihood of successful guidewire crossing within 30 min based on 5 criteria (intralesion >45° bend, length >20 mm, calcification, blunt stump, and previously failed attempt) (27). The J-CTO score has been validated in other CTO PCI cohorts (28) and is also associated with 1-year clinical outcomes (29), although prior failure was not associated with lower success rates in another study (30). Other scores include the PROGRESS-CTO (PROspective Global REgiStry for the Study of Chronic Total Occlusion Intervention) score (31), the RECHARGE (REgistry of Crossboss and Hybrid Procedures in FrAnce, the NetheRlands, BelGium and UnitEd Kingdom) registry score (32), the CL score (Clinical and Lesion related score) (33), and the ORA (ostial location, collateral filling of Rentrop <2, age over 75 years) score (34). Ellis at al. (35) used a novel approach for developing a scoring system for predicting CTO PCI technical success by stratifying lesions according to proximal cap ambiguity. Parameters associated with technical success were poor distal target, lesion length ≥10 mm, and ostial location in CTOs with proximal cap ambiguity versus worse collateral score and excess retrograde tortuosity in CTOs without proximal cap ambiguity (35). One study showed that various scores had similar predictive capacity for technical success and that they performed better in antegrade-only cases (36).

CTO PCI success scores should ideally be used for estimating success in patients and operators similar to the ones used for their development. They may be of most value for less experienced operators for selecting which cases to perform and which to refer or perform with a proctor. Moreover, they can assist with procedural planning (e.g., scheduling multiple highly complex CTO PCIs on the same day should be avoided).

COMPLICATIONS. CTO PCI is associated with higher risk for complications as compared with PCI

FIGURE 2 Perforation Management Algorithm



The first step in management of coronary perforations is balloon inflation to stop bleeding into the pericardium, followed by fluid/vasopressor administration, pericardiocentesis in case of hypotension and notification of cardiac surgery in case emergency surgery is needed. If the perforation is not sealed further management depends on perforation type: large vessel perforations are usually treated with a covered stent whereas distal vessel perforations are treated with embolization. Anticoagulation should not be reversed until all equipment is removed from the coronary arteries to minimize the risk for coronary thrombosis. Reproduced with permission from Brilakis (6).

of non-CTO lesions (26). The average risk is approximately 3%, but varies widely between studies (Table 1). Patient-specific risk estimates can be calculated by using a dedicated scoring system, such as the PROGRESS-CTO complications score that uses 3 variables (age ≥65 years, lesion length >23 mm, and application of retrograde approach) (37). Ellis et al. (35) reported the following 2 independent correlates of complications: moderate to severe lesion calcium, and low left ventricular ejection fraction.

Perforation. Coronary perforation is the most feared complication of CTO PCI (38) and our understanding of its diagnosis and treatment has significantly evolved in recent years. Coronary perforations during CTO PCI can be classified as large vessel, distal vessel, and collateral vessel perforations (6). The first step in any coronary perforation is inflation of a balloon to prevent additional bleeding into the pericardium (Figure 2). Subsequent treatment of large vessel perforations is usually achieved with covered stents and for distal vessel perforations with fat or coil embolization. Delivery of a covered stent was traditionally achieved using a dual guide catheter technique (balloon inflation through one guide catheter to tamponade the perforation and advancement of a covered stent through a second guide catheter). With development of lower profile covered stents (rapid exchange Graft-Master, Abbott Vascular, Santa Clara, California), both a balloon and a covered stent can now be delivered through a single 8-F guide catheter ("block-and-deliver" technique) (39). Similarly, for distal vessel perforation balloon occlusion and coil or fat delivery can be achieved through a single guide catheter (40). Collateral vessel perforation can be challenging to treat (22,41): epicardial collateral perforations require treatment from both directions to achieve sealing usually with coils, fat, or thrombin (42).

Coronary perforations in prior CABG patients have traditionally been considered less perilous, due to the belief that pericardial adhesions would prevent development of tamponade. Newer reports suggest that perforation in prior CABG patients may actually carry increased risk for major complications, because pericardial adhesions may result in formation of loculated hematomas that can cause localized tamponade and cardiogenic shock. Such hematomas are not amenable to drainage by pericardiocentesis and computed tomography-guided drainage or surgery may be required to drain the effusion (43–45). Intramural bleeding should be considered if there is no pericardial effusion by echocardiography, but the clinical picture is suggestive of pericardial tamponade (46).

Side branch occlusion and myocardial infarction. CTO lesions involve bifurcations frequently (in approximately a third of cases) (47). Side branch occlusion can affect both the acute and the long-term outcomes of CTO PCI and is more frequent with dissection reentry (both antegrade and retrograde) techniques and stenting over the side branch (48). PCI of CTOs that involve a bifurcation has also been associated with higher risk for perforation and tamponade (49).

Myocardial infarction during CTO PCI is more common with use of the retrograde approach (50,51) and has been associated with worse subsequent clinical outcomes in most (52–54) studies.

Radiation skin injury. CTO PCIs are often long procedures with high patient (and operator) radiation dose (55). High radiation dose may lead to acute dermatitis of the exposed area that can progress to chronic skin ulcer and even require surgical intervention. In a study of 2,124 patients undergoing 2,579 PCIs (including 238 CTO PCIs), a chronic skin ulcer developed in 0.34% (9 patients, 5 of which were CTO PCIs with skin lesion onset after 1 to 3 months of interventions) requiring surgical intervention in 8 of them (56). Most operators currently recommend stopping the procedure after reaching 7- or 8-Gy air kerma dose. It is also recommended to monitor the patient for radiation skin injury if >4- or 5-Gy air kerma dose is administered. With use of newer x-ray equipment, low cine and fluoroscopy frame rate, and meticulous attention to technique, radiation dose can be significantly reduced (57). Additionally, the use of disposable sterile radiation shields during CTO PCI can reduce operator radiation dose to levels similar to those of non-CTO PCIs (58).

RISK-BENEFIT RATIO. The decision about whether to perform CTO PCI should be individualized, starting with a thorough clinical and angiographic assessment to determine the potential clinical benefit (symptom improvement in most cases), likelihood of success, and risk for complications. CTO PCI should be offered to patients who have more to gain than to lose (**Central Illustration**).

CTO PCI TECHNIQUES

ACCESS SITE. Access site selection is important in CTO PCI for providing appropriate support, and allowing enough space for simultaneous use of multiple devices. Many operators recommend 8-F guiding catheters, mostly via transfemoral access, even though they may carry higher risk for vascular complications (59). Fluoroscopic guidance before puncture using surgical forceps was associated with ideal access position in >93% of 528 patients undergoing CTO PCI, and low (0.89%) incidence of adverse events (60).

In one study transradial CTO PCI was effective in appropriately selected cases (61), however the more complex lesions were performed using bifemoral access. In another study that compared transradial (n = 280) and transfemoral (n = 305) CTO PCIs, although technical success was similar in the 2 access groups (74.6% vs. 72.5%; p = 0.51), complex (J-CTO score ≥3) cases performed using transradial access had significantly lower technical success rates than those done using transfemoral access (35.7% vs. 58.2%; p = 0.004) (62). Many operators are currently performing biradial CTO PCI using 7-F slender sheaths (Terumo, Somerset, New Jersey) or sheathless 8-F transradial guide catheters. Transradial access can and is increasingly being used for CTO PCI among expert transradial operators (63), but may be associated with lower success and efficiency (63), especially in complex cases.

CTO CROSSING TECHNIQUES. There are 3 major techniques for crossing CTOs: antegrade wire escalation, antegrade dissection or re-entry, and the retrograde approach (6). Algorithms, such as the hybrid algorithm (18) and the Asia Pacific CTO algorithm (http://apcto.club/apcto-algorithm/), have been developed for choosing the initial crossing technique based on the angiographic characteristics of the occlusion.

The retrograde approach carries higher risk for periprocedural complications as compared with antegrade only approaches. In an analysis from the PROGRESS-CTO registry the risk was 4-fold higher with retrograde versus antegrade cases driven by higher risk for myocardial infarction and perforation requiring pericardiocentesis (64). The risk is higher with use of epicardial as compared with septal collateral (22), hence septal collateral vessels and bypass grafts (65) are preferred for retrograde crossing, when available. The retrograde approach remains critical for achieving high success rates, especially in more complex CTOs (19,20), and is associated with favorable long-term outcomes (21).

The relative merits of antegrade wire escalation versus antegrade dissection/re-entry remain controversial. The hybrid algorithm currently recommends use of antegrade dissection or re-entry for ≥20 mm long lesions with clear proximal cap and good quality distal vessel; and antegrade wire escalation for <20 mm long lesions. The CrossBoss First trial

(NCT02510547) (66) was the first randomized trial comparing the 2 approaches and demonstrated similar crossing time, similar success and complication rates and similar equipment utilization and cost in the 2 study groups. However, crossing was faster with the CrossBoss catheter in patients with CTOs due to in-stent restenosis. Similar to retrograde crossing, antegrade dissection or re-entry is more frequently used in more complex lesions (20,28). Extensive dissection or re-entry strategies, such as subintimal tracking and re-entry carry increased risk for periprocedural myocardial infarction due to side branch loss (67) and high restenosis and reocclusion rates and are currently only used as bailout (68).

IMAGING. Intravascular imaging is used in CTO PCI to guide crossing and for stent optimization. Intravascular ultrasound (IVUS) can help determine the location of the proximal cap, direct the guidewire within the occlusion and confirm distal true lumen position after crossing (67,69). Use of IVUS for CTO crossing can be challenging and requires expertise in image interpretation as well as use of large guide catheters that can accommodate the IVUS probe together with microcatheters and guidewires.

The role of IVUS for stent optimization during CTO PCI was recently evaluated in 2 randomized trials. Kim et al. (70) randomized 402 patients undergoing CTO PCI to IVUS guidance (n = 201) or angiographic guidance alone (n = 201) and reported lower incidence of MACE in the IVUS-guided group (2.6% vs. 7.1%; p = 0.0035; hazard ratio: 0.35; 95% confidence interval: 0.13 to 0.97). The AIR-CTO (Study comparing Angiography- vs. IVUS- and/or FFR-guided stent implantation for chronic total occlusion in coronary artery) study randomized 230 patients to IVUS-guided (n = 115) versus angiography-guided (n = 115) stent implantation after successful CTO crossing. During a follow-up of 12 months IVUS use was associated with lower in-stent late lumen loss (0.28 ± 0.48 mm vs. 0.46 ± 0.68 mm; p = 0.025), in-stent restenosis (3.9% vs. 13.7%; p = 0.021), and stent thrombosis (0.9% vs. 6.1%; p = 0.043) (71). Similar to non-CTO lesions, achieving good stent expansion is associated with lower rates for restenosis (72).

The role of coronary computed tomography angiography (CTA) in CTO PCI continues to evolve. Scores have been developed to predict CTO PCI success based on coronary CTA characteristics and measurements (73); however, further evaluation are needed in larger patient cohorts. Fusion of coronary CTA-derived images with coronary angiography during PCI could potentially facilitate CTO crossing attempts. Kim et al. (74) used coronary CTA imaging to localize the guidewire within the lesion in 61 patients, and their method proved to be helpful in identifying not just single antegrade wires, but parallel or retrograde wires as well. Cases performed with coronary CTA coregistration tended to have higher technical success (83% vs. 63%; p = 0.147).

In summary, imaging can play a significant role in CTO PCI for procedural planning (coronary CTA), guiding CTO crossing (coronary CTA and IVUS), and optimizing the final stent result (IVUS), that can translate into better long-term outcomes.

OPTIMAL STENTING IN CTO PCI. Restenosis after CTO PCI with bare-metal stents was approximately 50%, but with use of drug-eluting stents, clinical outcomes have significantly improved with low rates of restenosis, reocclusion, and target vessel revascularization (75). The vessel distal to the occlusion often enlarges after restoration of antegrade flow (76), suggesting that residual distal stenoses post–CTO PCI that do not affect antegrade flow may not require stenting. Few cases of "crushing" a previously implanted stent after substent crossing have been reported with promising mid-term results, but further assessment is required to understand the long-term outcome of this technique (77–79).

TRAINING AND EDUCATION. Given the complexity of CTO PCI, becoming and remaining successful CTO operator requires appropriate training and continued practice, both for achieving high success rates (23) and also for minimizing the risk for complications and efficiently managing them if they occur (25,26). Optimal training for CTO PCI remains controversial, as there are few dedicated fellowship programs. Most operators learn CTO PCI after being in practice for a few years through participation in courses and proctoring. In a study of 587 CTO PCIs, operators who were proctored in the hybrid approach had higher procedural success (77.5% vs. 62.1%; p < 0.0001), especially in more complex cases (J-CTO score ≥2: 70.7% vs. 49.5%; p = 0.0003), with similar periprocedural complication rates. Furthermore, they were more willing to perform CTO PCI, even in complex occlusions (J-CTO score ≥3: 15% before vs. 30% after proctorship; p < 0.0001) (80).

Live case demonstrations are an integral part of CTO PCI courses raising concerns for adverse patient outcomes. Shimura et al. (81) compared the outcomes of live case demonstrations of CTO PCI (n = 199) with cases that were not performed live (n = 540). Procedural success (91.5% vs. 86.7%; p = 0.076), 30-day mortality (0% vs. 0.7%; p = 0.28), and complications rates, such as dissection (p = 0.53), perforation (p = 0.12), or cardiac tamponade (p = 0.40), were similar in the 2 groups, suggesting that live case demonstrations are safe.

In summary, upfront training and continuous education through publications, online resources (e.g., www.ctomanual.org, www.ctofundamentals.org and http://apcto.club/apcto-algorithm/), live case demonstrations, CTO PCI workshops, and proctorships are essential for acquiring, maintaining, and improving the operators' skills, leading to higher success and lower complication rates.

CONCLUSIONS

CTO PCI is a rapidly evolving field. With improvement in equipment and techniques, high success rates can be achieved at experienced centers, although success rates remain low in unselected centers, a gap that needs to be bridged through innovation and education. Prospective, randomized-controlled data regarding optimal use and indications of CTO PCI remain limited. Further high-quality studies of CTO PCI are needed, as well as expansion of expert centers and operators that can achieve excellent clinical outcomes in this challenging patient-and-lesion subgroup. In the meantime, thoughtful and detailed consideration of the potential risks and benefits of the procedure (**Central Illustration**) can optimize clinical decision making for each individual patient with coronary CTOs.

ADDRESS FOR CORRESPONDENCE: Dr. Emmanouil S. Brilakis, Minneapolis Heart Institute, 920 East 28th Street #300, Minneapolis, Minnesota 55407. E-mail: esbrilakis@gmail.com.

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