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Algorithmic solutions to common problems encountered during chronic total occlusion angioplasty: The algorithms within the algorithm

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Abstract

Improved technical equipment, dissemination of best practices, and the importance of complete coronary revascularization have led to a renewed interest in coronary chronic total occlusion (CTO) PCI. In particular, the hybrid algorithm has been associated with increasing procedural success rates in the US. However, the hybrid algorithm only covers overarching strategies in the overall approach to these lesions. Several technical challenges can occur during execution of these approaches, each of which has several potential solutions. A systematic or algorithmic approach to dealing with these challenges could contribute to improved procedural efficiency and higher procedural success. While there have been isolated attempts in the past to codify approaches to each of these situations, there has not been a contemporary, comprehensive review of the potential solutions to these problems. We present 10 common problems encountered during CTO PCI and a consensus hierarchical approach to them.

KEYWORDS

consensus, percutaneous coronary intervention, solutions

The hybrid algorithm for selecting crossing strategies for coronary chronic total occlusions (CTOs) was initially reported in 2012 via consensus of high volume CTO PCI operators (Figure 1) [1]. In essence, the algorithm is predicated on four angiographic features seen on dual catheter angiography: (1) anatomy of the lesion's proximal and distal caps, (2) anatomy of the vessel distal to the lesion's distal cap, (3) the presence of useable collaterals, and (4) the length of the lesion occlusion segment. The first three inform the operator whether to start

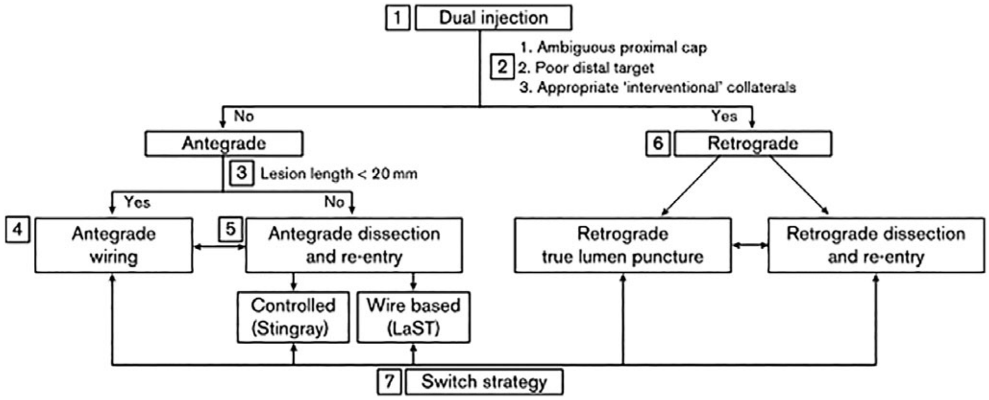


FIGURE 1 The hybrid algorithm

anterograde (well-defined proximal cap with a distal landing zone after the distal cap suitable for re-entry) or retrograde (ambiguity about the location of the proximal cap, major side branches at the proximal or distal cap and/or a poor distal landing zone, along with appropriate collaterals). The length of the lesion then guides the operator as to whether to attempt wire escalation or to move toward subintimal reentry, although it has been recently proposed that subintimal strategies should only follow failed wire escalation strategies [2]. Since its publication, use of the algorithm has been associated with increased CTO PCI adoption, procedural efficiency, and success rates [3–7].

However, the hybrid algorithm only describes the overall approach to crossing these lesions (directionality and intimal versus subintimal crossing). There are also several common technical challenges that can occur during implementation of these various approaches that have their own individual treatment algorithms. Table 1 is a list of 10 of the most common problems encountered during CTO PCI. While there have been individual attempts to describe some of these challenges and their solutions in the past, these have been limited to small case series or single technical reports. This review describes a comprehensive, hierarchical review of contemporary solutions to these challenges in consensus recommended order based on accumulated experience to provide a framework for continued education in CTO PCI. While the authors have striven to put these solutions in logical order to promote simpler, safer, and more cost-efficient maneuvers as initial steps, we recognize that this organization is based on limited retrospective data and encourage clinical judgment in their implementation.

TABLE 1 Common problems encountered during chronic total occlusion percutaneous coronary intervention

Wire impenetrable cap
Wire will cross cap/lesion but gear won't follow
Cap ambiguity
Proximal cap ambiguity
Distal cap ambiguity
Difficult anterograde dissection re-entry
Wire across retrograde collateral but microcatheter will not follow
Septal collateral
Bypass graft collateral
Epicardial collateral
Difficult retrograde dissection re-entry
Cannot externalize wire during retrograde dissection re-entry
Wire/gear keeps going into a side branch around/within a lesion
Difficult suture line to cross
In-stent chronic total occlusions

1 | WIRE IMPENETRABLE CAP ALGORITHM

This problem often occurs while attempting to penetrate the proximal cap, though it can occur with the distal cap as well, especially in post-CABG patients. This section focuses on the strategy for approaching an impenetrable proximal cap (Table 2), though many of these methods will work for an impenetrable distal cap as well, though some will be more difficult to implement from the retrograde approach.

This algorithm assumes that standard maneuvers have been implemented to maximize support and that the strongest, tapered-tip penetration wires that are available have also failed to penetrate the cap. Steps for maximal guide support include deeply intubating the guide ("amplatzing" the guide) into the coronary, using a guide extension, and/or utilizing an anchor balloon either in a proximal side branch or a stented area in another vessel if possible (e.g., stented proximal circumflex for a CTO lesion in a LAD or vice-versa), as shown in Figure 2.

The first potential solution is BASE ("Balloon-Assisted Subintimal Entry") power knuckle. Note that this strategy depends on being able to complete either an anterograde dissection and re-entry (ADR) or retrograde dissection and re-entry (RDR) procedure. If these options are not available to the operator, consider alternative options. This maneuver consists of two parts. The first step is BASE, which gains entry into the subintimal space, followed by use of a power knuckle to get around the cap. First, leave the MC utilized during wire escalation in-place. Then bring in 1:1 sized noncompliant (NC) balloon into the

TABLE 2 Wire impenetrable cap solution algorithm

1. Balloon-Assisted Subintimal Entry (BASE) power knuckle
2. Scratch-and-go
3. Carlino
4. Laser atherectomy
5. Go retrograde

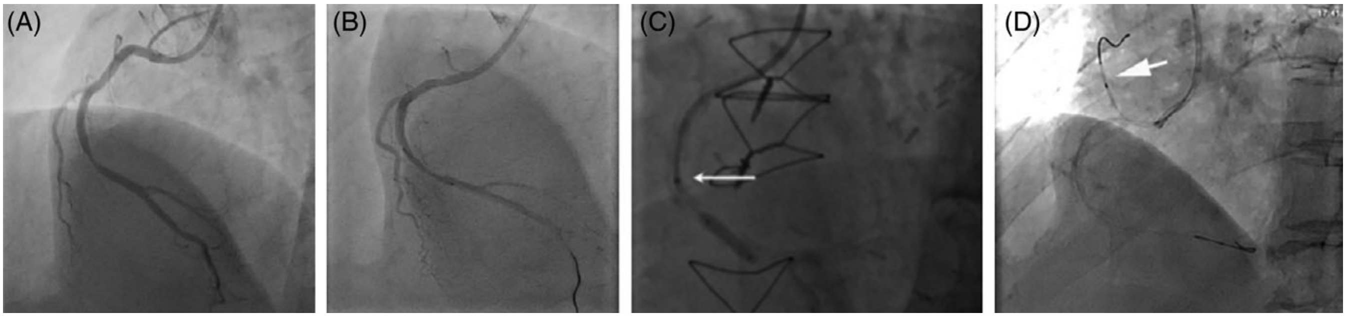


FIGURE 2 Ways to increase guide support. Panels A and B show before and after amplatzing a guide; panel C shows use of a guide extension (arrow); panel D shows use of an anchor balloon in a proximal branch of an RCA (arrow)

vessel over a workhorse wire placed in the vessel proximal to the impenetrable cap. Inflate the balloon proximal to the cap several times to a size 1:1 with the vessel, ideally at the site of plaque if possible; an NC balloon is utilized as it has a higher likelihood of creating a dissection compared to a semi-compliant balloon. The goal here is to create a dissection in the vessel architecture proximal to the cap in order to enter the subintimal space ("BASE"). After BASE, it is usually easiest to facilitate wire passage into the sub-intimal space by "trapping" the MC parallel to the middle segment of the inflated balloon by inflating the balloon. A polymer jacketed wire is then pushed into the subintimal space to form a knuckle proximal to the cap, subsequently bypassing the impenetrable cap; it is termed a "power knuckle" due to the additional support afforded by the inflated balloon next to the MC (Figure 3). If the wire makes satisfactory progress into the vessel architecture, the balloon is deflated and the MC advanced as normal. One caveat for using BASE in this scenario is that it relies on having a sufficient length of vessel proximal to the impenetrable cap to deploy a balloon. In very proximal or ostial lesions, this may not be feasible.

A similar solution is termed a "scratch-and-go" (Figure 4). The idea behind this maneuver is using a stiff wire to penetrate into the vessel architecture immediately proximal to the impenetrable cap to gain access to the subintimal space, which facilitates the gear traversing through the subintimal space and around the cap in the true lumen, similar to BASE. Step one is the scratch: a stiff tapered-tip penetration wire is used to puncture into resistant tissue in the vessel wall architecture proximal to the cap. Confirmation of location of the wire tip within the vessel architecture (ensuring the wire tip is "dancing" with the target vessel segment) should be done in multiple views and can be aided by the presence of calcium. After ensuring the wire tip and vessel architecture are moving in-phase in multiple views, advance the MC tip just into the vessel wall architecture (no more than 1–2 mm). The second step is "and-go": once the tip of the MC is just into the architecture of the vessel wall, switch out for a polymer jacketed wire and knuckle the wire in the subintimal space into the distal vessel architecture and set up for distal reentry distal to the distal cap in typical fashion. Switching out for a knuckle as soon as possible will minimize the risk of wire exit outside of the vessel architecture, while also confirming wire presence in the vessel architecture of the CTO body prior to advancing secondary equipment. In contrast to BASE, where dissection is blunt, the scratch-and-go method relies on forceful penetration with sharp wires. It is imperative that these stiff wires are not advanced over long distances to minimize the risk of wire perforation. Most importantly, secondary equipment (e.g., MC, balloons) should not be advanced until wire position is confirmed in the vessel architecture.

A third solution is termed a "Carlino", named for Dr. Mauro Carlino, who first reported the procedure [8]. It involves a hydraulic

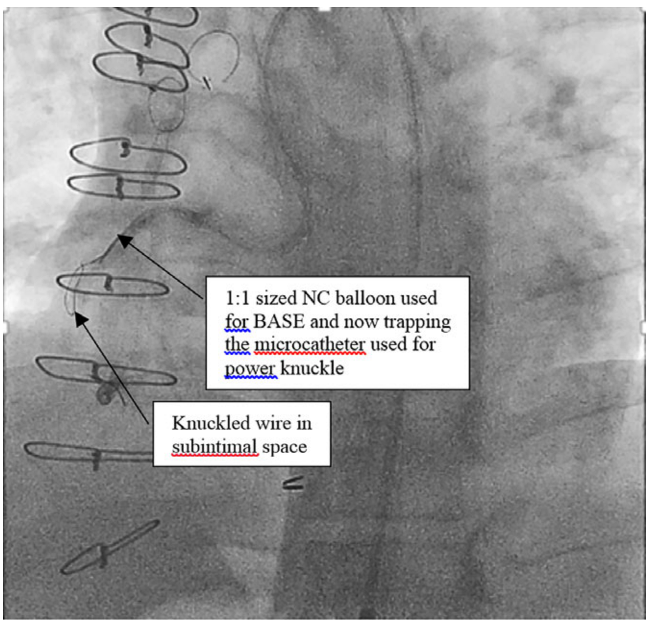


FIGURE 3 Example of Balloon-Assisted Subintimal Entry ("BASE") Powerknuckle [Color figure can be viewed at wileyonlinelibrary.com]

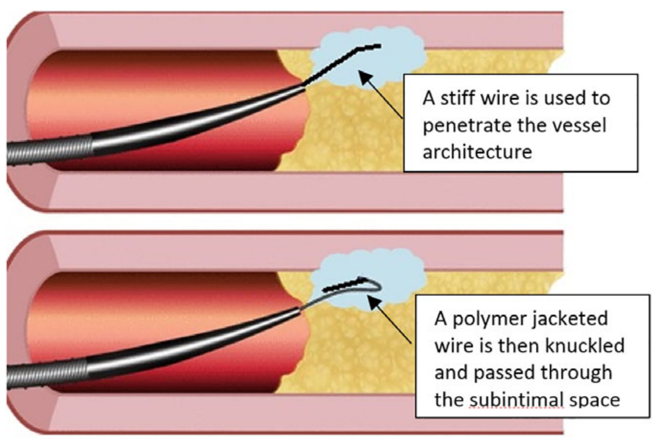


FIGURE 4 Example of a scratch-and-go [Color figure can be viewed at wileyonlinelibrary.com]

microdissection of the cap by injection of a small volume of contrast (<1 mL) through a MC using a high-pressure 2 cm^3 luer-lock syringe with the tip of the MC positioned on the proximal cap. The injection should be performed in a controlled manner and under fluoroscopic guidance to ensure that the injection does not extend to creating a true perforation out of the adventitia of the vessel. After this maneuver, reintroduce a stiff wire and reattempt to puncture the proximal cap using conventional wire escalation. It is useful to remember whenever contrast is introduced in an MC, the wires can become sticky due to the viscosity of the retained contrast; this can be overcome by flushing the MC with heparinized saline after the injection, prior to reinserting a wire.

A fourth solution is using a laser catheter to soften up the proximal cap, much as the Carlino injection is intended to do. Start by bring in a 0.9 mm laser catheter to the tip of the wire at the proximal cap and then perform laser atherectomy on the cap, typically from 30 sec to several minutes. After laser atherectomy is complete, bring in a MC over the wire and attempt to puncture the cap again using conventional wire escalation, similar to after the Carlino maneuver.

A final solution for an impenetrable cap if the previous four solutions fail is to go retrograde. For cases in which the retrograde approach is favorable, this step may occur sooner in the algorithm. Typically, the distal cap of the CTO is softer and easier to puncture compared to the proximal cap, possibly due to chronic exposure to collateral-supplied pressures versus the systemic pressures the proximal cap is exposed to. From a retrograde approach, it is often possible to cross the proximal cap, either by retrograde wire escalation or subintimally around the resistant segment. If a wire is able to traverse past the resistant cap and lumen re-entry is not achieved from a retrograde direction, it may also be possible to perform an "external" cap crush by delivery of a balloon retrograde and inflating it at the site of the resistant cap, crushing the cap, and then re-attempt anterograde strategies (see section 2).

2 | WIRE ACROSS CAP/LESION BUT GEAR WILL NOT FOLLOW ALGORITHM

A second common problem encountered in CTO PCI is when the wire crosses the proximal cap or other resistant area within the lesion but a MC will not follow. This is most commonly seen in a heavily calcified and/or post-CABG lesion. The solutions to this problem are listed in Table 3. These solutions can be grouped into those that involve working over the original wire that crossed the cap and those that involve sacrificing wire position.

3 | WORKING OVER THE INITIAL WIRE

The simplest solution is increasing guide support, as previously mentioned. If increasing guide support does not allow for advancement of the MC through the cap/lesion, a next step would be to switch the MC out for a 1.0, 1.2/1.25, or a 1.5 mm × 20 mm semicompliant balloon. This balloon is advanced as distally as possible. Serial high-pressure inflations are then performed with this balloon in an attempt to advance it through the lesion. If successful in advancing the balloon though the lesion, switch out for the MC and proceed as normal. The reason for using a 20 mm length balloon in this situation is that the largest diameter of the profile for balloons <2 mm is the dot marking the central portion of the balloon (as opposed to 2.0 mm and larger balloons that have markers on each end of the balloon). Therefore, the longer length of the lower profile portion of these smaller balloons prior to the central marker will allow them to be advanced further than 2.0 mm and larger balloons. One caveat is that if this problem is encountered while retrograde, balloons with longer shafts (e.g., Trek [Abbott]) may be required in order to have the necessary length to reach the occlusion.

TABLE 3 Wire across cap/lesion but gear will not follow solution algorithm

1. Increase guide support
2. Small balloon inflations
3. Balloon-Assisted Microdissection (BAM)
4. Switch to smaller profile microcatheter
5. Switch to stiffer microcatheter
6. Laser atherectomy
7. External cap crush
8. Carlino
9. Deliver a short roto wire and perform rotational atherectomy
10. Go retrograde
11. See wire impenetrable cap algorithm

If these balloons will not advance, a next step could be BAM (Balloon-Assisted Microdissection aka "Grenadoplasty"). During this maneuver, the lower profile balloon that was initially used to try to cross is now taken to the point it will no longer advance and then inflated carefully until it deliberately ruptures in an attempt to create a microdissection of the resistant area of the lesion. This must be done in a careful manner under fluoroscopy, with quick deflation of the balloon as soon as burst is noted by rapid loss of pressure in the insufflator and/or noting burst under fluoroscopy via the flash of contrast from the balloon rupture in order to reduce risk of vessel perforation from the rupture of the balloon. This is also why this maneuver should not be done with larger profile balloons. After the intentional balloon rupture, a second low profile balloon or MC can be brought in to reattempt lesion crossing.

After attempting BAM or if BAM does not work, switching out for a lower profile MC (Caravel [Asahi], Turnpike LP [Vascular Solutions]) can be considered. If these will not cross, a stiffer MC can be tried, such as a Tornus (Asahi) or Turnpike Gold (Vascular Solutions). If this does not work, laser atherectomy of the cap/lesion with a 0.9 mm laser catheter can be performed, as previously described.

Another method is to consider in this situation is an external cap crush (Figure 5). The reason that a wire will cross a lesion and then the MC will not follow often occurs when the initial wire is in the true lumen with too much resistance from the plaque in the lumen, limiting the ability for the MC to cross. In order to overcome this, a second wire/MC system can be taken into the subintimal space, "external" to the lesion in the true lumen, and used to modify ("crush") the resistant area. There are three steps to this procedure. First, with the initial

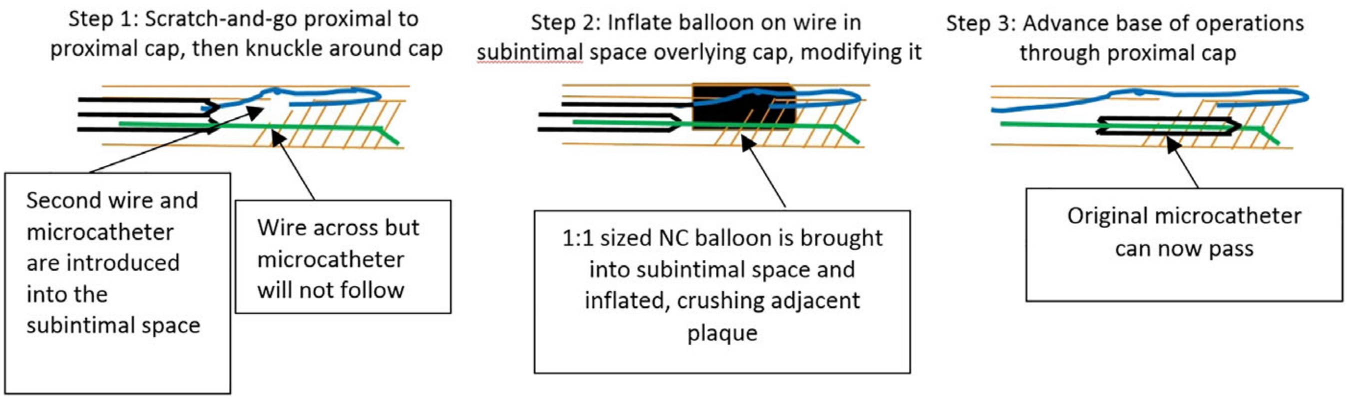


FIGURE 5 External cap crush [Color figure can be viewed at wileyonlinelibrary.com]

wire left in-place, perform a scratch-and-go or BASE with a second wire/MC system proximal to the cap, then switch out for a low gram force polymer jacketed wire and knuckle this wire around the resistant cap/lesion in the subintimal space. Then, switch out the MC on the knuckled wire for a 1:1 sized NC balloon and take the balloon in the subintimal space to the site of the resistant cap/lesion in the true lumen, then inflate it to match the size of the vessel, thereby "crushing" the cap/lesion and modifying it from the subintimal space. Then, remove the NC balloon out of the subintimal space and attempt to move an MC over the original wire past the previously resistant site.

4 | SOLUTIONS THAT REQUIRE SACRIFICING THE INITIAL WIRE POSITION

These steps should only be performed if the above steps, which allow retention of wire position are not successful. The first of these steps is performing a Carlino maneuver at the resistant site to try and alter the plaque in the resistant segment. If unsuccessful, the final antero-grade step involves rotational atherectomy over a knuckled or shortened Rota-Floppy wire (Boston Scientific). This is achieved by advancing an MC (preferably low-profile) as far as possible over the index wire. The original wire is removed from the distal vessel. The Rota-Floppy wire is then advanced as far as possible into the CTO segment beyond the MC, ideally, on a distal knuckle to move the radio-opaque segment well beyond the area where plaque modification is planned. If this is not feasible, the wire can be modified by cutting the majority of the radio-opaque segment off (although still retaining enough for the tip to be visible on fluoroscopy), thereby allowing the 0.014″ radio-opaque segment to move sufficiently far beyond the area planned for atherectomy. Very focused rotational atherectomy is then performed and limited to the resistant segment only [9]. This technique has been used safely in the intimal and subintimal space [10]. If these techniques fails, revert to the "Wire Impenetrable Cap" algorithm or switch to a retrograde approach.

TABLE 4 Proximal cap ambiguity solution algorithm

1. Go retrograde
2. IVUS-guided puncture of cap if side branch is available
3. Side Balloon-Assisted Subintimal Entry (S-BASE)
4. Balloon-Assisted Subintimal Entry (BASE) power knuckle
5. Scratch-and-go
6. Coronary computed tomographic angiography

5 | CTO CAP AMBIGUITY ALGORITHMS

5.1 | Proximal cap ambiguity

At times, there will be ambiguity regarding the anatomic site of one of the caps of a CTO lesion. This can be due to branches around the cap, bypass grafts at the cap site, poor visualization from angiography, etc. The algorithm for solving proximal cap ambiguity can be seen in Table 4. An initial solution to solving proximal ambiguity is to bring in a wire and MC retrograde to define and mark the vessel course with either a wire or knuckle that is brought close to or past the proximal cap to serve as a marker for the vessel course and to direct the anterograde wiring attempt.

If unable to go retrograde, a second solution involves utilizing IVUS to resolve the ambiguity of the cap location if a side branch is present that is close enough to the cap and large enough to pass an IVUS catheter into. The side branch is wired and an IVUS catheter advanced into the branch. A pullback will often illustrate the site of the cap (Figure 6). If an adequate diameter guide catheter is in place, the IVUS can be left in situ and a MC and wire can then be brought into the vessel in parallel to attempt to puncture the cap under direct IVUS visualization.

Another method of using the side branch to resolve vessel ambiguity is Side-Balloon-Assisted Subintimal Entry ("S-BASE", Figure 7). This maneuver involves taking a semicompliant balloon (sized 1:1 with the side branch) over a wire in the side branch and inflating it to extend from the side branch into the proximal vessel. With the balloon inflated, a looped polymer jacketed wire is pushed through a MC in the main vessel proximal to the bifurcation. The inflated balloon will deflect this knuckled wire away from the side branch and into the main vessel. This maneuver has the benefit of preserving the side branch and resolving vessel ambiguity [11].

If a retrograde approach is not feasible and no major side branch is present in the vicinity of the cap, proximal cap ambiguity can also be solved with either a BASE power knuckle or scratch and go in order to get into the subintimal space at an unambiguous site in the vessel

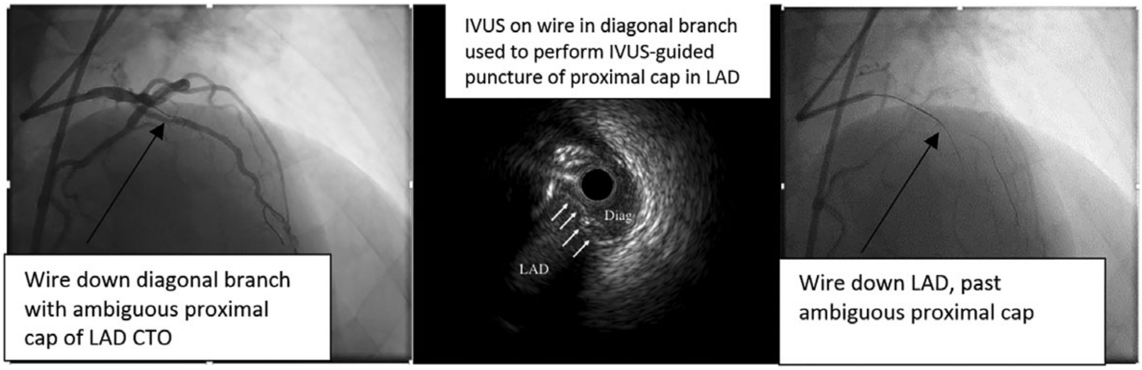


FIGURE 6 Example of IVUS-guided resolution of LAD CTO proximal cap ambiguity by performing IVUS over a wire in a diagonal branch and identifying the proximal cap at the bifurcation of the LAD and diagonal branch (arrows)

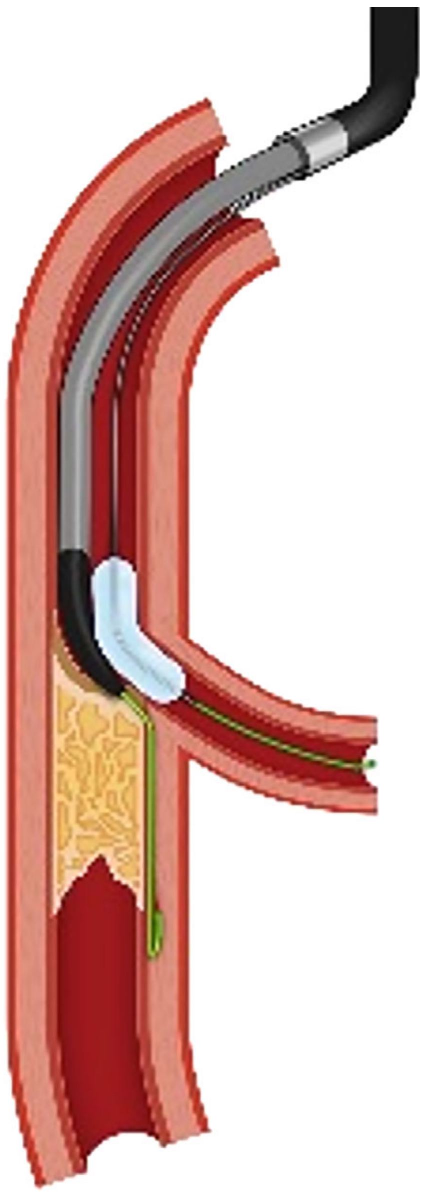


FIGURE 7 Illustration of side-BASE (S-BASE) [Color figure can be viewed at wileyonlinelibrary.com]

architecture proximal to the cap, allowing subintimal knuckling within the vessel architecture around the ambiguous cap site. If all of these methods fail or the ambiguity is anticipated preprocedurally, coronary computed tomography angiography (CCTA) may be useful in order to lay out the trajectory of the vessel and direct the initial or subsequent attempt.

5.2 | Distal cap ambiguity

The algorithm for solving distal cap ambiguity can be seen in Table 5. This scenario is common in post-CABG patients where the distal cap is close to or lies on a graft suture line and the wire/equipment continues to migrate into the graft instead of the native epicardial vessel. An initial way to solve this problem is with a distal MC tip injection using contrast and a 2 cm^3 luer-lock high-pressure syringe. As contrast is injected, withdrawal of the MC will often illustrate the distal cap and graft anastomosis if present. This can then direct the next attempt to puncture the distal cap. It may also result in staining of the subintimal space (essentially a retrograde Carlino maneuver), which can provide the operator with a map of the vessel to track. If this does not work, an anterograde knuckle can be advanced into the distal vessel architecture to the ambiguous segment. This can be used as a marker for retrograde wire advancement, solving the anatomic ambiguity of the distal cap, similar to the method used to solve proximal cap ambiguity described above.

Another solution is to perform BASE over the retrograde wire, creating a dissection distal to the cap, and then switching out for a polymer jacketed wire to knuckle retrograde within the subintimal space to solve the ambiguity. It is always safer to solve anatomic ambiguity with knuckles versus directional wiring given that the

TABLE 5 Distal cap ambiguity solution algorithm

1. Retrograde microcatheter distal tip injection
2. Mark distal vessel course with anterograde knuckle and then use stiff, tapered wire retrograde to puncture into vessel architecture
3. Retrograde Balloon-Assisted Subintimal Entry (BASE), then switch out for knuckle
4. Leave retrograde balloon in-place for controlled anterograde and retrograde tracking and dissection (CART) or facilitated anterograde dissection reentry (ADR)
5. Coronary computed tomography angiography

knuckles will track the vessel architecture while wiring alone is more prone to perforate the vessel. During any of these maneuvers, there is always the option of leaving the retrograde wire in-place and bringing in a retrograde balloon into the distal vessel and performing controlled anterograde and retrograde tracking and dissection (CART) or facilitated ADR, as previously described [12,13]. Finally, if these methods fail, CCTA can be performed to lay out the trajectory of the vessels to inform the initial or subsequent attempt.

6 | DIFFICULT ANTEROGRADE DISSECTION REENTRY ALGORITHM

ADR is unsuccessful in ~30% of cases [1]. Given this, we have developed an algorithm to address this common problem, as seen in Table 6. If the initial Stingray MC (Boston Scientific) has been correctly deployed at the target landing zone but wire puncture into the true lumen fails, then "bob-sledding" can be attempted. This involves deflating the Stingray catheter and moving it over a stiff wire reintroduced through the distal lumen of the catheter and into a more favorable location within the vessel architecture (less calcium, closer to the true lumen, less tortuous, less hematoma), either proximal or distal to the previously attempted site, and then reattempting ADR at this location.

Failure to puncture with a Stingray wire may also be overcome by the use of an appropriately shaped specialist CTO penetration wire (e.g., Confianza Pro12 [Asahi], Hornet 14 [Boston Scientific], Astato 20 or 40 [Asahi]) in order to fenestrate into the distal lumen. The concept here is that stiffer wires with different tip bends can puncture into the true lumen when the pre-bent Stingray wire (Boston Scientific) fails to do so. This step can be performed as a "stick-and-drive" using the specialist CTO penetration wire or by "stick-and-swap" where the vessel is punctured by the specialist CTO penetration wire and then switched out for a polymer-jacketed medium gram force wire, which is used to enter the distal true lumen through the puncture made by the specialist CTO penetration wire.

A common reason ADR fails is due to hematoma formation in the subintimal space, which compressed the true lumen, and makes re-entry into this space more difficult. A solution to this problem is Subintimal TRAnscatheter Withdrawal (STRAW) of the subintimal space. This is achieved by a number of potential steps. The simplest is placing a syringe with negative pressure on the over-the-wire port of the Stingray catheter prior to performing the stick-and-drive or stick-and-swap. This can be left attached for several minutes for blood to be withdrawn from the space around the reentry site. STRAW can also be performed by introducing a parallel OTW balloon into the vessel over a second wire system; this balloon should be sized 1:1 with the vessel. The balloon is taken into a vessel segment just proximal to the proximal cap of the CTO, inflated, and then after wire removal, a syringe is attached to the proximal port for continuous suction of blood from the subintimal space. This method blocks the inflow and reduces hematoma, facilitating re-entry [14].

TABLE 6 Difficult anterograde dissection re-entry (ADR) solution algorithm

1. Bob-sled
2. Using a stiffer, tapered wire for stick-and-go or stick-and swap
3. Subintimal transcatheter withdrawal (STRAW) via stingray or a OTW balloon
4. Wire re-direct into a different subintimal plane closer to the true lumen and attempt ADR at this new location
5. Go retrograde to set up for retrograde dissection re-entry
6. Limited Anterograde Subintimal Tracking (LAST)
7. Subintimal tracking and re-entry (STAR) or subintimal plaque modification

The next solution to this problem could be to wire redirect into a different subintimal plane (ideally closer to the true lumen) and then re-set up ADR. If this fails, leave the anterograde wire and MC in-place and switch to a retrograde strategy to set up for RDR.

If these methods fail, LAST (Limited Anterograde Subintimal Tracking) can also be attempted at this point, where the subintimal space is fenestrated into the true lumen with a stiff wire several times, followed by wiring the true lumen with a medium weight polymer jacketed wire. This is very similar to the approach utilized with the Stingray catheter, though this method is less successful than ADR using a Stingray catheter [15]. IVUS can also be helpful in guiding LAST. To perform this, an IVUS catheter is advanced over the subintimal wire and used to determine the location of the true lumen. A second wire/MC system is then taken into the subintimal space next to the first system and a stiff wire is used to puncture into the true lumen under IVUS guidance - this is similar to IVUS-guided parallel wiring [2].

Finally, if the procedure has failed both anterograde and retrograde approaches (or retrograde is not a possibility), then a Subintimal Tracking And Reentry (STAR) procedure can be performed [16]. The goal here is to advance a deliberately knuckled wire anterograde and let it re-enter the true lumen distally, usually at a bifurcation; this will be noted by a quick shrinkage of the knuckle as it moves from the subintimal to luminal space (be sure to store the fluoroscopy images noting this reentry location). The knuckle is then followed by the MC to dotter the entry into the true lumen, followed by predilating the lesion and subintimal space past the reentry site of the knuckle into the true lumen to ensure outflow. Studies have shown that performing a STAR with adequate outflow (≥2 branches distal to the reentry zone), leaving the vessel to heal for several weeks, and then bringing the patient back for repeat PCI attempt will result in recruitment of more distal branches and in shorter segments that require stenting compared to stenting during the initial STAR procedure [16,17]. Alternatively, if the distal knuckle fails to re-enter the true lumen distally, subintimal plaque modification can also be performed, as previously described, which has been shown to be independently associated with better patient-reported health status at 30 days [18].

7 | WIRE ACROSS RETROGRADE COLLATERAL BUT MICROCATHETER WILL NOT FOLLOW ALGORITHMS

Performing a retrograde CTO procedure requires both successful wiring and MC passage through the retrograde channel, whether septal, epicardial or bypass graft. If the wire is able to negotiate the channel but the MC is unable to follow, there are several solutions, depending on the channel used.

7.1 | Septal algorithm

The solutions for septal microcatheter issues can be seen in Table 7. Resistance occurs most frequently at the inferior portion of the septum or when a very proximal first septal connects circuitously (and sometimes epicardially) into the posterolateral branch. Assuming a meticulous MC spin technique is being utilized, the initial solution is to increase guide support, as previously described in the "Wire Impenetrable Cap" algorithm. The next approach is to inflate a 1.0, 1.2/1.25 or 1.5 × 20 mm balloon at low pressures at the resistant spot in the septum, then re-attempt crossing with the MC. If unsuccessful, exchange for a lower profile MC. If these will not pass, dottering the retrograde channel with a 135 cm MC may provide more torsion to dilate the channel, with subsequent exchange back for the 150 cm device. Alternatively, if the retrograde wire has progressed sufficiently into the lesion, anterograde equipment can be brought to the same segment and a balloon inflated to trap the retrograde wire and provide a better rail for delivery of the retrograde MC. Finally, if a softer wire (e.g., Sion or Suoh03 [Asahi]) has been used to cross the channel, attempting to rewire with a wire with a stiffer body (e.g., Fielder FC [Asahi]) may provide a stiffer rail to take the MC across. If none of these solutions are successful, switching to another collateral or to an anterograde strategy may be necessary, leaving the retrograde wire as a marker for the distal vessel to facilitate anterograde approaches or CART.

7.2 | Bypass graft algorithm

MC challenges in bypass grafts often occur at the retroflexed turn of the distal anastomosis. Solutions to this scenario can be seen in Table 8. Guide support assumes an even greater role when a graft is used as the retrograde channel. Preloading the guide catheter with a guide extension prior to wire and MC crossing is recommended. If the MC is not making the turn, using a stiffer wire and/or a lower profile MC should be attempted. If unsuccessful, a second wire can be advanced down the graft into the distal limb of the grafted vessel, and a 1:1 sized semi-compliant "blocking" balloon can be inflated just distal to the anastomosis to help support the retrograde MC as it is making the turn. Alternatively, if the retrograde wire has progressed sufficiently into the lesion, anterograde equipment can be brought to the same segment and a balloon inflated to trap the retrograde wire and provide a better rail for delivery of the retrograde MC, as noted above.

TABLE 7 Wire across retrograde septal collateral but MC will not follow

1. Increase guide support with guideliner, amplatz guide, anchor balloon
2. Balloon septal with 1.0, 1.2/1.25 mm (or 1.5) × 20 mm balloon
3. Dotter channel with 135 cm MC, then switch back to 150 cm MC
4. Use lower profile MC
5. Switch out for stiffer wire
6. Try another collateral
7. Go anterograde, leaving retrograde gear for controlled anterograde and retrograde tracking and dissection (CART) or facilitated anterograde dissection reentry (ADR)

TABLE 8 Wire across bypass graft collateral but microcatheter will not follow

1. Increase guide support
2. Wire escalation
3. Lower profile microcatheter
4. Blocking balloon in distal grafted vessel
5. Trap retrograde wire with anterograde balloon

7.3 | Epicardial algorithm

The solutions for having a wire across an epicardial collateral but the MC will not follow can be seen in Table 9. There are fewer options for solving this issue due to the more fragile nature of epicardial collaterals and higher risks from a perforation compared to septal or bypass graft collaterals—this is why balloon dilation of the epicardial vessel is more dangerous than for septals and should be avoided. The solutions involve increasing guide support, followed by using a lower profile MC. If these two solutions do not work, the final strategy is trying another collateral or switching back to an anterograde strategy, leaving the retrograde wire as a marker in the distal vessel.

8 | DIFFICULT RETROGRADE DISSECTION REENTRY (R-CART) ALGORITHM

A common issue that arises during R-CART involves the inability to make the connection between the retrograde and anterograde equipment. The solutions to this scenario can be seen in Table 10. The most frequent reason the connection cannot be made is under-sizing the balloon used to make the connection. This can be solved by bringing in an IVUS catheter on the anterograde wire to visualize the size of the vessel and subsequently appropriately size the balloon (1:1 sized with vessel size) used to facilitate making the connection. IVUS can also be used here to see if the anterograde and retrograde equipment are in the same space (true lumen versus subintimal) or differing spaces, which can also change the method of making the connection (differing spaces often requires a stiffer wire to puncture the subintimal tissue plane that separates the two systems). If IVUS is not an option, the balloon can be serially upsized given the high likelihood that the original balloon was undersized.

The next solution is to use a higher penetration wire with a longer bend to penetrate the tissues plane that may be between the two sets of equipment. The safety of this step can be enhanced by placing a guide extension over the anterograde equipment in order to leave as short a distance as possible for the stiff wire to traverse. A third

TABLE 9 Wire across retrograde epicardial collateral but microcatheter will not follow

1. Increase guide support
2. Use lower profile microcatheter
3. Try a new collateral or go anterograde

TABLE 10 Difficult retrograde dissection reentry (R-CART)

1. IVUS-guided sizing of balloon used to make connection and identify locations of anterograde and retrograde gear
2. Use higher penetration wire with longer bend
3. Use of anterograde guide extension
4. Move re-entry point proximally or distally
5. Switch to controlled anterograde and retrograde tracking and re-entry (CART) or facilitated anterograde dissection re-entry (ADR)

solution is to move the point where the connection is being made either more proximally or distally depending on where the two systems appear to be closest together along the length of the vessel.

If these methods fail, the retrograde MC can be exchanged for a balloon and left in the distal vessel as a marker for CART. Another solution that utilizes a balloon on the retrograde wire in the distal vessel is "facilitated ADR", where the retrograde balloon is used as a marker for the true lumen to guide reentry during ADR [13].

9 | INABILITY TO EXTERNALIZE WIRE DURING R-CART ALGORITHMS

9.1 | Retrograde wire is in anterograde guide but the MC will not follow

This section will cover the scenario when the retrograde equipment (wire or wire plus MC) is in the anterograde guide/guide extension during R-CART but there are difficulties externalizing the wire through the anterograde guide. It is not uncommon to manipulate the retrograde wire into the anterograde guide then discover that the MC will not follow easily. This can be due to a combination of factors including plaque burden within the CTO or MC fatigue and/or damage due to the friction within the system.

Solutions to this problem are listed in Table 11. An initial solution is to inflate a trapping balloon in the anterograde guide (appropriately sized for the guide/guide extension), pinning the retrograde wire. This enables tension to be put on the retrograde wire to rail the retrograde MC into the anterograde guide. This is obviously not possible when a single guide and an ipsilateral collateral channel has been crossed. Inserting a second guide and wiring it will allow this balloon anchoring technique to be performed in the case of an ipsilateral retrograde approach. This is often referred to as using "ping pong" guides [19].

TABLE 11 Inability to externalize wire during reverse controlled anterograde and retrograde tracking and re-entry (R-CART)

Retrograde wire is in anterograde guide but microcatheter will not follow
1. Inflate a trapping balloon in anterograde guide fixing the retrograde wire
2. Switch out for fresh or new type (coiled versus braided) of microcatheter
3. Modify resistant segment with anterograde balloon inflation
4. Balloon dilate the collateral channel and CTO segment with retrograde balloon
5. Rewire with a 300 cm wire for externalization
6. Tip-in
7. Controlled anterograde and retrograde tracking and re-entry (CART) or facilitated anterograde dissection re-entry (ADR)
Retrograde MC in anterograde system but unable to externalize
1. Switch type of externalization wire between R350 to RG3
2. Roto glide in microcatheter for lubrication
3. Tip-in in aortic arch with a fielder XT3
4. Balloon retrograde channel
5. Controlled anterograde and retrograde tracking and re-entry (CART) or facilitated anterograde dissection re-entry

If the MC cannot cross despite these techniques, it is possible that the MC may have been damaged or "fatigued" in the process of getting retrograde access and through the distal cap. Significant vessel tortuosity and/or excessive manipulation of the MC can lead to kinking of the MC, especially if it is a coiled MC (Corsair [Asahi], Turnpike [Teleflex]). The tip of the MC can also become blunted or damaged passing through the distal cap and through the CTO segment. Switching to a fresh MC in this situation should be considered early. One way that MCs can be classified is as braided (Finecross [Terumo], Caravel [Asahi]) which have lower crossing profile but are nontorquable versus coiled (Corsair, Turnpike), which have a larger crossing profile but are torquable and more robust. Switching from a braided to a coiled MC may allow additional push through the CTO (assuming the crossing profile allows delivery). However, sometimes switching from a coiled to a braided MC may remove enough friction from the system to allow the MC to track more freely.

If a new MC still will not pass, consider a retrograde balloon inflation at the site where the MC is getting stuck to disrupt the CTO segment. Balloons with long shafts (140–150 cm), such as a Trek (Abbott) are preferable for this maneuver. After dilation, switch back to the MC. If the MC is close to the anterograde catheter and a good connection has been made, then re-wiring with a long (>300 cm) wire may facilitate externalization. Often the MC fails to advance in this situation due to the degree of plaque burden especially if it is calcified. Bringing in an anterograde balloon (even in the subintimal space) can modify the plaque/vessel at the site where the MC is failing to cross and may allow the MC to advance.

If these methods fail, wiring an anterograde MC with the retrograde wire ("tipping-in") can be performed (Figure 8). This is best achieved on the outer curvature of the anterograde guide, though this can also successfully be performed in the coronary as well. The anterograde MC is then advanced over the retrograde wire as the retrograde MC is withdrawn. If these methods fail, a retrograde balloon can be brought in for CART or facilitated ADR.

9.2 | When the retrograde MC has reached the anterograde guide, but the externalization wire will not progress

Once the MC is in the anterograde guide or guide extension, an externalization wire is typically inserted to complete the case. The common externalization wires used are the R350 (0.013″, 350 cm wire, Vascular Solutions), which has a stiffer, nitinol body and the steel-bodied RG3 wire (0.010″, 330 cm, Asahi). However, sometimes it is not possible to externalize the wire due to friction within the system. Switching between externalization wires is an option to overcome this problem. The R350 is more pushable and less prone to kinking but is thicker, whereas the RG3 has a lower profile and creates less friction but can

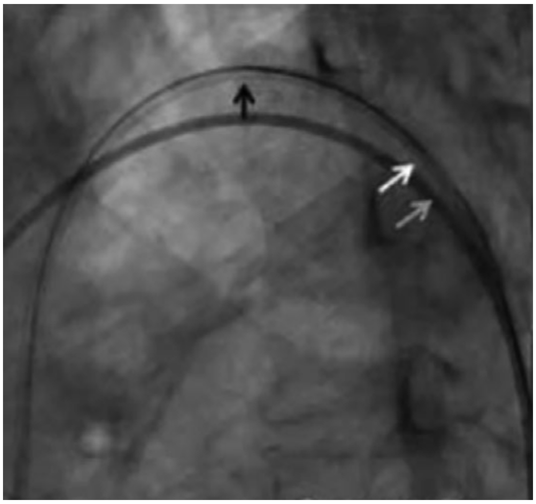


FIGURE 8 Example of tip-in in the aortic arch. The two white arrows indicate a microcatheter being advanced anterograde while the black arrow represents a wire being advanced retrograde though the same guide. The most likely place they will meet in the guide is in the aortic arch, where they will both hug the outer curvature of the guide. Once they meet, the microcatheter can be slid over the wire and into the vessel until the wire comes out of the distal end of the microcatheter

be less pushable and may be more prone to kink. Another solution is to inject a lubricant such as RotoGlide (Boston Scientific) through the retrograde MC and attempt to externalize again.

If these maneuvers are still unsuccessful, tip-in can be performed as described previously. Alternatively, an anterograde trapping balloon can also be used in this situation to trap a short wire or long wire that is not fully externalized from the retrograde MC within the anterograde guide. This will allow removal of the retrograde MC, followed by subsequent balloon dilation of the retrograde channel to reduce the friction points. A further switch out for a new retrograde MC may allow for externalization. Finally, the retrograde MC position can be sacrificed, and the device withdrawn. The MC can be swapped for a retrograde balloon to facilitate CART or facilitated ADR.

10 | WIRE/GEAR TRACK INTO A SIDE BRANCH AT A CAP OR WITHIN A LESION ALGORITHM

A side branch is a common finding in mature occlusions, either at the site of the proximal cap or within the lesion [20]. It can create technical problems for recanalization by masking the main epicardial vessel course (ambiguity) and/or reducing the penetration force of the wire into the main vessel (the side branch creates a side load on the wire, thereby reducing the force of penetration into the CTO body). While the hybrid algorithm suggests a retrograde approach for CTO lesions where the proximal cap is either ambiguous (often due to a side branch) or when a major side branch exists at the cap, there will be situations where either the retrograde approach is not an option or has been failed and an anterograde approach that involves a side branch is required. The various solutions to this problem can be seen in Table 12.

TABLE 12 Wire/gear track into a side branch at a cap or within a lesion algorithm

1. Wire-redirect with a longer bend on a penetration wire to direct away from the side branch and into the main vessel
2. Dual lumen catheter over wire in side branch
3. IVUS into side branch to define location of CTO in main epicardial
4. Side Balloon-Assisted Subintimal Entry (S-BASE)
5. Knuckle with pilot 200 to bypass branch
6. Balloon-Assisted Subintimal Entry (BASE) power knuckle proximal to bifurcation
7. Scratch-and-go
8. Carlino to define where you are and to cause dissection into main epicardial
9. Retrograde access with retrograde equipment acting as marker for anterograde puncture

An initial solution to this problem is putting a longer bend on the wires being used for cap penetration in order to direct away from the side branch and into the lesion. A dual lumen MC can also be used in this situation to significantly aid in redirection and augment penetration force. To utilize a dual lumen MC in this situation, a workhorse wire is placed in the side branch and the dual lumen MC advanced so that the OTW port aligns with the CTO cap. Wire escalation can then be performed through the OTW port to puncture the cap. IVUS can be helpful in this scenario as well to both define the location of the main vessel and to direct the wire penetration under live visualization. Another method of using the side branch to bypass the CTO cap and resolve vessel ambiguity is S-BASE, as previously described in the proximal cap ambiguity section above.

Other solutions exist that can put the side branch in jeopardy. The simplest is knuckling a Pilot 200 wire (Abbott) proximal to the side branch and using the larger size of the Pilot 200 knuckle to direct away from the smaller lumen of the side branch and toward the large lumen of the main epicardial vessel. An alternative is to perform a BASE power knuckle or scratch-and-go proximal to the bifurcation in order to enter the subintimal space prior to the bifurcation and therefore stay out of the side branch. A Carlino injection can also be performed to define where the bifurcation is and create a dissection into the main vessel in order to better inform a reattempt at a wire redirect with a longer tip bend. If all of these steps fail, the anterograde gear can be left as a marker in the proximal vessel and retrograde gear brought past the side branch takeoff, then using the retrograde gear as a marker for anterograde puncture with a stiffer penetrating wire.

11 | DIFFICULTY CROSSING DUE TO GRAFT INSERTION (SUTURE LINE) ALGORITHM

In post-CABG patients, crossing graft insertions can be difficult due to the fibrotic nature of suture lines. The strategy for crossing the sutures shown in Table 13 starts with wire escalation, followed by wire escalation from the opposite direction (try retrograde puncture if started anterograde or vice-versa) as these suture lines may not have homogenous fibrosis. If resistant to wire escalation from both directions, a Carlino injection from one or both directions can also be used

TABLE 13 Difficulty crossing due to graft insertion (suture line) solution algorithm

1. Switch to retrograde approach if failing anterograde or anterograde if failing retrograde
2. Bilateral Carlino to define anatomy and try to dissect suture line
3. Laser atherectomy of the suture line
4. Balloon-Assisted Subintimal Entry (BASE) from either direction
5. Knuckle a Confianza Pro12/hornet 14 if can't wire escalate across from either direction

to cause micro-dissections in the suture lines and soften them up for subsequent wire escalation. Laser atherectomy at the suture line can also be performed here as the laser can often soften the suture line up for subsequent wire escalation, similar to the procedure described in the wire impenetrable cap algorithm above. Another option is to try BASE power knuckle proximal to the suture line to try and go around the suture line. If these methods fail, a stiff, tapered wire can be knuckled past the suture line, followed by immediate deescalation to a jacketed, tapered wire to ensure you are still within the vessel architecture and without vessel perforation.

12 | IN-STENT CTO ALGORITHM

CTOs that include in-stent restenosis can provide specific challenges. The various solutions for CTOs involving stents are shown in Figure 9. The solution depends on whether the caps are within, proximal, or distal to the stent, as shown. For lesions with both caps contained in the stent, a CrossBoss (Boston Scientific) is an excellent initial strategy as it will likely cross the distal cap in-stent [21]. If the CrossBoss will not advance through the stented segment (often due to a stent strut or edge), it can be wire-redirected into the CTO body. If the CrossBoss does not penetrate the proximal cap, or stalls within the CTO body (often occurs in marked tortuosity) then it is usually necessary to switch out for a MC and wire. On occasion, medium polymer weight jacketed wires will progress in the lesion, although high penetration force tapered wires are often needed. It is important that orthogonal X-ray views are taken as the wire progresses in order to ensure that progress remains within the stent architecture and does not weave in and out of stent struts. If the MC progresses, then pursuing further wire-based crossing is reasonable, though the CrossBoss can be reintroduced to complete the lesion crossing here as well.

For lesions with the proximal cap in-stent and the distal cap beyond the distal stent edge, the approach depends on whether the distal cap is at a bifurcation. If not, starting with a CrossBoss is reasonable. The CrossBoss should be advanced beyond the distal cap, with luminal position checked via gentle advancement of a workhorse wire. If the device has passed to the sub-intimal space, Stingray-based ADR can be performed. However, if the distal cap is at a bifurcation, a retrograde approach is typically preferred in an attempt to preserve the bifurcation, as directed by the hybrid algorithm. Retrograde wire escalation can then be attempted if the distance of the segment from the stent edge to the distal cap bifurcation is short. Alternatively, for longer lesions (>20 mm), R-CART can be completed in the segment distal to or within the stent, after crossing the proximal cap within the stent architecture.

If the proximal cap of the CTO is proximal to the proximal stent edge with the distal cap in-stent, wire escalation or knuckling to the proximal stent edge can be performed, using the stent as a marker to puncture into the stent with a stiff wire. Once position is confirmed within the stent, the MC cab be exchanged for a CrossBoss, which is advanced past the distal cap, finishing by confirming position in the true lumen of the distal stent with a workhorse wire. Alternatively, R-CART could be performed proximal to or in-stent.

Finally, if both the proximal and distal caps extend beyond the stent, it is recommended to attempt to wire into the stent from whichever direction is most feasible. Wire escalation or dissection re-entry can be completed subsequently. However, if unable to stay within the stent architecture (often due to mechanical issues within the stent such as underexpansion, fracture, etc.), a final strategy is to wire or knuckle around the old stent and crush it out of the way, usually by R-CART, completing the case by stenting alongside the old stent [22].

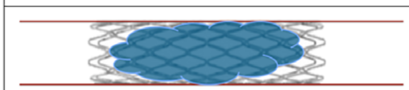
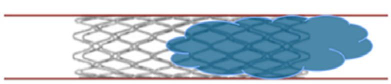
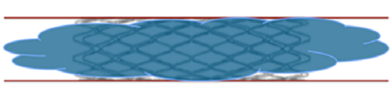
	Proximal cap	Distal cap	Recommended strategy
	In-stent	In-stent	1. CrossBoss
	In-stent	Distal to stent	1. CrossBoss with wire escalation or dissection re-entry if distal cap not at bifurcation 2. Wire escalation or dissection re-entry distal to or inside of stent if distal cap is at bifurcation
	Proximal to stent	In-stent	1. Wire into stent, then CrossBoss 2. Reverse CART inside of or proximal to stent
	Proximal to stent	Distal to stent	1. Wire into stent from either direction (Anterograde or retrograde) and perform wire escalation or re-entry 2. Wire escalation or dissection re-entry around old stent, crushing old stent, then stenting around crushed old stent

FIGURE 9 Solutions for CTOs involving in-stent restenosis [Color figure can be viewed at wileyonlinelibrary.com]

13 | CONCLUSION

Dissemination of the hybrid algorithm for CTO crossing strategies has been associated with improved CTO PCI procedural success rates. However, many common challenges remain during CTO PCI that are not addressed by the hybrid algorithm. This review addresses many of these challenges and provides consensus hierarchical solutions to these problems by multiple high-volume CTO operators, adding to the growing technical body of literature addressing these complex procedures.

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