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# Acute coronary complications in chronic total occlusion interventions

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intervention

Chronic total occlusion (CTO) interventions are among the most complex procedures within the panorama of percutaneous coronary intervention (PCI). Awareness of potential complications, adequate procedural planning in order to avoid them, and prompt recognition and management should any occur are at the cornerstone of a successful CTO programme. Complications can be acute or late after the procedure and can be cardiac or non-cardiac. Acute cardiac complications can occur directly at the coronary artery level or can have other strictly non-coronary manifestations, such as hypotension, myocardial infarction, arrhythmias, or tamponade. In this review, we focus on acute coronary complications of CTO PCI, in particular their causes, prevention, and management strategies.

## Introduction

Chronic total occlusion (CTO) percutaneous coronary intervention (PCI) represents today a valuable tool within the armamentarium in the treatment of coronary artery disease. As with any other therapy in the medical field, especially when dealing with invasive procedures, the decision to pursue CTO PCI depends on its anticipated benefit and estimated risk. When clinically indicated, it can provide patients with significant benefits, including relief from symptoms, improvement in quality of life, offer of revascularization options to poor candidates for coronary artery bypass grafting, reduction in myocardial ischaemia, improvement in myocardial function, prevention of arrhythmias and, possibly, improvement in long-term survival. Nonetheless, the increased risk for complications after CTO PCI than after non-CTO PCI needs to be acknowledged.[1] Complications can occur early (that is procedural, or acute) and at long-term follow-up. Acute non-cardiac complications can be related to vascular access, thromboembolic events, contrast medium-related kidney injury, and radiation injury. Among cardiac complications, hypotension, myocardial infarction, arrhythmias, and tamponade are not direct coronary manifestations. On the other hand, acute coronary complications can be integrated into three main categories, i.e. vessel closure, perforation and equipment entrapment, or loss,[2] can have different aetiologies and can occur at any of the following locations: aorto-coronary, main vessel, side branch, distal vessel, collaterals, and donor vessel (*Figure 1*). The present review deals with acute coronary complications, and we will focus on their causes, prevention, and treatment strategies (*Table 1*).[3]

## Vessel closure

As introduced above, acute vessel closure can occur at any point in the coronary tree throughout the procedure. While the closure of the main target vessel downstream or upstream of the occlusion in absence of involvement of any relevant side branch might not be clinically significant, given that by definition CTO stands for target vessel occlusion for at least the past 3 months, closure of other

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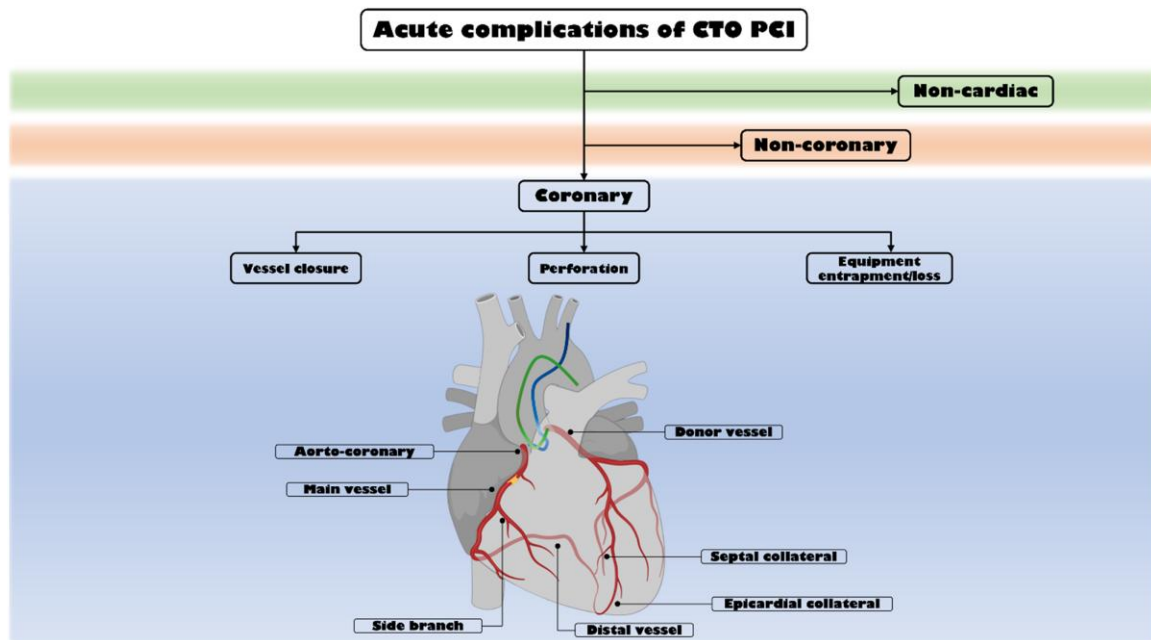
**Figure 1** Acute complications of CTO interventions. Acute coronary complications include vessel closure, perforation, and equipment entrapment or loss. Examples of non-cardiac and non-coronary complications are reported in the text.

vessels can impact the clinical picture to different degrees. The main mechanisms of vessel closure are:

- Dissection;
- Thrombosis;
- Embolization (air, thrombus, aortic, iliac, or coronary plaque).

Numerous factors need to be acknowledged when planning CTO PCI in order to avoid acute coronary complications, and include extent of donor vessel disease, catheter-induced vessel injury, guidewire choice, manipulation and location, control of contrast injection, balloon and stent implantation features, crossing strategy, activated clotting time (ACT), and appropriate device flushing. Back-bleeding the guide catheter (GC) after insertion and trapping are the basis of thrombotic and embolization complications prevention. Also, ACT should be targeted to >300 and >350 s for antegrade and retrograde CTO PCI, respectively. Procedural management of such complications includes techniques not strictly related to CTO PCI, that is aspiration (either through aspiration catheter, GC extension, or deeply engaged GC), 100% oxygen administration (in case of air embolism), and, possibly, intracoronary adrenaline.[2] On the other hand, complications related to coronary dissection often require specific CTO PCI expertise and will be the focus of the following section. We will address the most common clinical scenarios, their implications, prevention, and management strategies.

## Donor vessel
Donor vessel closure may occur when instrumented for contralateral angiography or retrograde approach, due to either catheter-related injury or vessel thrombosis. The former may occur especially during equipment withdrawal or pulling on the retrograde snared guidewire, while the latter may be exacerbated by long procedures with much intraluminal hardware (*Figure 2*). It represents one of the most clinically relevant complications of CTO PCI, and this is particularly true when the donor vessel represents the last remaining vessel.[4] It is, therefore, of paramount importance to assess procedural risk for each single patient, and evaluate the possibility to augment procedural safety by the implementation of prophylactic haemodynamic support in particular high-risk settings including patients with multivessel disease and low left ventricular ejection fraction.

## Planning
Avoidance of catheter-related vessel injury and donor vessel thrombosis requires a proper pre-treatment plan, involving considerations on donor vessel selection, overall strategy, catheter, and guidewire choice and manipulation:

- Retrograde approach should be avoided through diseased donor vessels unless PCI is planned ahead, and through a left internal mammary artery, due to risk of dissection or concertina phenomenon;[5]
- Adequate position of diagnostic and GC (i.e. not too deep) is essential, as is an appropriate pressure wave with no dampening. Thus, catheters with side holes should be avoided in the donor vessel, as they may hide suboptimal catheter position.
- In particular, position of the retrograde catheter should be confirmed upon guidewire externalization and during procedural steps performed on the wire loop to avoid deep GC engagement. Conversion from retrograde to the antegrade system by kissing microcatheter or tip-in techniques should thus be considered as soon as feasible.
- Additional care via retrograde guidewire encasement within a microcatheter or over-the-wire balloon can

**Table 1** Acute coronary complications in CTO PCI. Factors to consider, prevention, and treatment strategies for main acute coronary complications that may occur during CTO PCI are outlined

| Acute complication | Factors to consider | Prevention | Treatment |
|---|---|---|---|
| **Vessel closure (dissection, thrombosis, and embolization)** | | | |
| Donor vessel | Donor vessel disease Catheter-related vessel injury GW choice, manipulation, location Contrast injection Balloon/stent sizing/ pressure/location Crossing and revascularization strategy ACT | Retrograde approach through adequate donor vessel Catheter position, type, and size optimization GW choice and manipulation Retrograde to antegrade system conversion | Stenting Thrombus aspiration/gpIIbIIIa |
| Aortocoronary | | Catheter position, type, and size optimization Controlled contrast injection | Stop standard contrast injection Stenting Serial non-invasive imaging Emergency surgery |
| Side branch | Equipment flushing | Anatomy and collateral circulation evaluation Crossing strategy choice Protection GW in side branch Guidewire position check | Antegrade/retrograde wiring (±IVUS) Reentry techniques |
| Collateral | | GW choice and manipulation Avoid too small or tortuous vessels | Stenting Thrombus aspiration/gpIIbIIIa |
| Distal vessel | | Reentry techniques Controlled contrast injection GW choice and manipulation | STRAW Retrograde crossing Investment procedure |
| **Perforation** | | | |
| Main vessel | Equipment advancement Balloon/stent sizing/ pressure | Equipment advancement Balloon/stent sizing/pressure GW choice and manipulation | Prolonged balloon inflations Covered stent |
| Distal vessel | GW choice and manipulation Collateral vessel features | GW choice and manipulation Trapping or guidewire extension > Nanto's | Embolization ('block and deliver') Covered stent over origin of perforated branch |
| Septal collateral | | Avoid too small or tortuous vessels Avoid aggressive equipment advancement Avoid aggressive vessel dilation Back-bleeding sign upon tip injection Keep guidewire in before removal | (Often self-limiting) Advance microcatheter Negative pressure Embolization |
| Epicardial collateral | | Contrast-guided wiring Avoid vessel dilation Tip-in if retrograde ipsilateral Keep guidewire before removal | Advance microcatheter Negative pressure Embolization (antegrade and retrograde) |
| **Equipment entrapment or loss** | | | |
| GW Microcatheter GC exchange RA burr Balloon Stent | Vessel features Antegrade/retrograde equipment relationship Retrograde equipment delivery | Avoid too angulated vessels Avoid too-aggressive equipment manipulation Antegrade balloon/stent impinged on retrograde microcatheter Adequate vessel preparation before stenting | GW: traction, trapping balloon, controlled rupture, snaring. Microcatheter: traction, shaft cut and GC exchange telescoping, balloon angioplasty, and snaring GC exchange: traction, trapping balloon, snaring. RA burr: shaft cut and GC exchange telescoping, balloon angioplasty Balloon: trapping balloon, shaft cut, and GC exchange telescoping Stent: snaring, small balloon, crush/ deploy |

Prevention refers to either the complication itself or of worsening of the clinical picture by prompt recognition of such complication.
GW, guidewire; RA, rotational atherectomy.
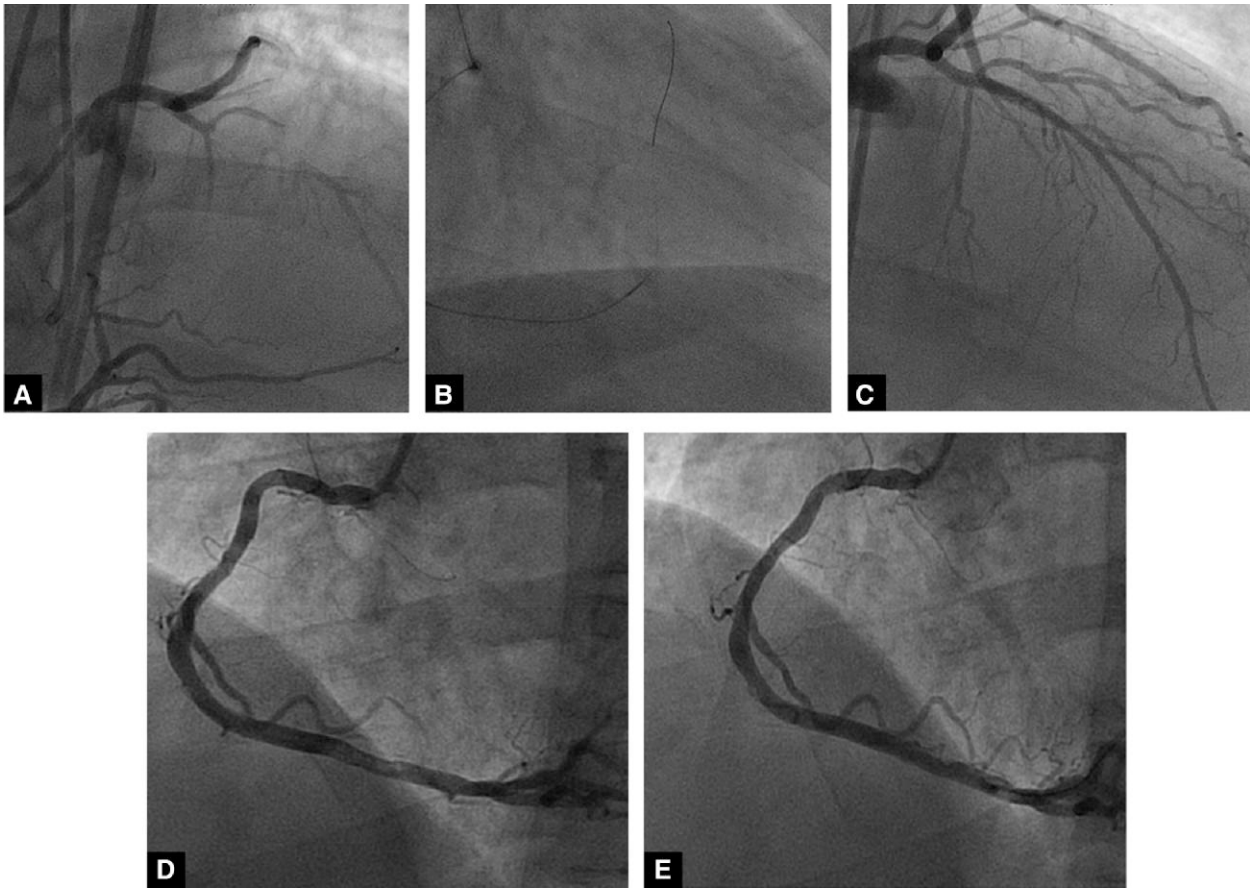
**Figure 2** Thrombotic donor vessel injury. A patient status post failed antegrade revascularization of a mid-left anterior descending artery (LAD) CTO (*A*) underwent a second successful procedure via contralateral retrograde approach through a septal channel (*B* and *C*). Thrombus was evident at final angiography in the distal segment of the RCA (*D*). Activated clotting time was maintained above 350 s and manual thrombus aspiration followed, with complete thrombus resolution (*E*). *Courtesy of Dr. R. Garbo.*

be implemented. Also, the insertion of an additional retrograde 'workhorse' safety guidewire may allow rapid management should donor vessel occlusion occur.

### Treatment

Upon acute donor vessel closure, CTO PCI should be, in most cases, aborted, and focus should be moved onto the donor vessel. Haemodynamic support devices should be prepared, if not already in place. Stenting is the treatment of choice in the setting of a dissection and, according to the strategy adopted and the timing within the procedure, can be performed according to different strategies. A 'workhorse' wire exchanged through the retrograde microcatheter positioned beyond the occlusion can be used if the CTO is not crossed yet. Instead, in case of an almost complete procedure, the stent can be delivered on either the externalized retrograde wire or a second additional wire advanced past the occlusion.

### Aorto-coronary

Aorto-coronary dissection occurs in about 1 out of 100 CTO PCI, is more common during retrograde procedures and involves more often the right coronary artery (RCA).[2,6] Similarly to donor vessel dissection, catheter-related vessel injury due to deep engagement and aggressive

catheters (e.g. 8 French Amplatzers) and uncontrolled contrast injection in presence of dampened pressure waveforms may result in vessel wall damage. Additional causes include coronary ostium predilation, with or without balloon rupture, and inadvertent retrograde wire advancement into the subintimal space.

### Planning

Risk of catheter-related vessel injury can be mitigated by adoption of anchor techniques in order to enhance catheter support rather than proceeding with deep engagement. The risk of barotrauma in occluded right coronary arteries may instead be decreased by contrast injection through catheters with side holes. In addition, after proximal target vessel dilation, manual injections should be preferred to those via power injectors.

### Treatment

The most important action to avoid expansion of the dissection plane is stopping injection of contrast within the coronary artery. Only if essential, injection through an aspiration catheter positioned in the distal part of the vessel may be considered. Stenting the ostium with a 1 mm protrusion into the aorta, preferably via intravascular ultrasound (IVUS) guidance is the treatment of choice in most
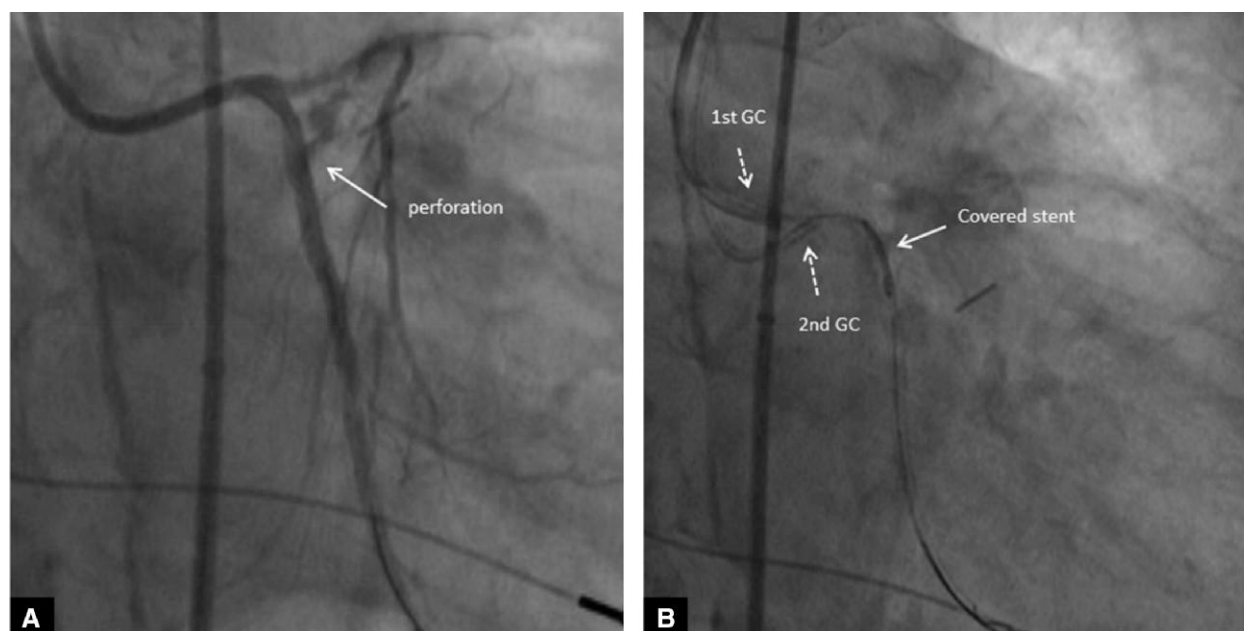
**Figure 3** Dual GC technique. Final angiography showed a type III Ellis perforation in the proximal left circumflex artery, which occurred after stent post-dilatation (*A*, white arrow). Illustration of an example of the dual GC technique (*B*, dotted arrows), in which a balloon is immediately delivered through the first GC to stop bleeding, whereas a second GC is inserted for covered stent delivery (see white arrow). Re-adapted from *Gasparini GL, et al. Cardiovasc Revasc Med. 2018;19(7 Pt B):879-886.*

cases. Additional follow-up via non-invasive imaging, preferably computed tomography, may be considered in presence of large flaps involving the ascending aorta. Finally, emergent surgery is indicated only in the rare case of significant dissection flap extension, aortic regurgitation, or tamponade.

## Side branch

Side branch occlusion is a potential complication of CTO PCI, especially when such branches arise close to the proximal or distal CTO cap. It can occur both when dissection and reentry crossing techniques are intentionally employed and also upon inadvertent dissection. Early recognition is key, since successive ballooning and stenting may render re-entrance in the true lumen troublesome.[7]

### Planning

Irrespective of the clinical scenario, treatment of a CTO involving a bifurcation should include a careful analysis of collateral support, for considerations on both the treatment plan and clinical impact in case of a branch closure.

In general, when planning CTO PCI, intentional dissection, and reentry crossing techniques should be avoided if a bifurcation is present at the proximal or distal CTO cap. In addition, location of the bifurcation with respect to the proximal or distal caps may aid in crossing technique selection, e.g. occlusion of a side branch close to the distal cap during antegrade crossing attempts may be avoided by the implementation of a primary retrograde approach. On the other hand, in case a dissection and reentry technique is undertaken, side branch protection with a second guidewire should be promoted, whenever possible.

Inadvertent vessel dissection may be prevented by a pondered judgment of guidewire position, and a low

threshold for suspicion should be maintained, especially when manipulating wire knuckles or aggressive guidewires (e.g. heavy tip tapered wires), before proceeding to ballooning and stenting. The following methods can be adopted:

- First, assessment of wire movement into distal branches may suggest gaining of the true lumen, even though this sign is non-specific, as subintimal wire advancement into side branches might also occur.
- Contralateral contrast injection is key after CTO crossing in almost all PCI, and intraluminal position should be checked in two orthogonal projections. This may be helpful also in presence of ipsilateral collaterals, as they might be compromised during crossing attempts.
- Controlled microcatheter tip injections should be performed in selected cases, always checking for back-bleeding to avoid subintimal staining and dissection propagation.
- Short-tip IVUS can also be of help in assessing distal wire location, while the need to perform injections with optical coherence tomography should discourage its employment.

### Treatment

Antegrade wiring of the occluded branch should be attempted, and IVUS guidance might be contemplated. Device-based reentry techniques, including stingray and re-cross, are likely the most controlled for aiming at reentry before side branch emergence. If failed, wire-based reentry techniques such as subintimal tracking and re-entry (STAR), miniSTAR, contrast-guided STAR, antegrade fenestration and reentry, and limited antegrade subintimal tracking could be considered as well.[8] Additional approaches include retrograde recanalization of the

occluded branch (if in presence of collaterals to that branch) in case of intentional dissection and reentry techniques and retrograde crossing of the target vessel in case of inadvertent target vessel dissection.

## Distal vessel

Distal vessel occlusion may occur secondary to subintimal haematoma formation in the setting of strategies including dissection and failed reentry attempts or to inadvertent manipulation of stiff or tapered-tip guidewires.

## Planning

Large guidewire loops should be avoided when planning subintimal dissection and reentry crossing techniques. In addition, utilization of devices, such as the Crossboss catheter, can aid to minimize the extent of distal dissection.

As noted earlier, it is key to avoid antegrade contrast injection upon guidewire entering into the subintimal space. In addition, the movement of stiff and tapered-tip guidewires should be limited by the adoption of equipment exchange techniques such as trapping or exchange wire.

## Treatment

Subintimal haematoma aspiration to favour distal true lumen re-expansion can be tempted according to the subintimal transcatheter withdrawal (STRAW) technique.[2] Otherwise, retrograde crossing can be considered. Finally, the operator can opt for an 'investment procedure', consisting of balloon angioplasty within the subintimal space, which might promote distal true lumen flow restoration at follow-up angiography.

## Collateral

Acute closure of a single large, usually epicardial, collateral is a potentially dramatic complication. Its clinical implications may be as important as those determined by acute donor vessel closure, depending on the degree of alternate collateral circulation. As such, a high threshold should be recognized before performing retrograde CTO PCI via such collaterals. Inadequate interventional collateral vessel characteristics and inappropriate guidewire choice and manipulation may favour mechanical injury to the vessel wall and dissection. Thus, in addition to the standard precautions in terms of ACT maintenance at target and regular device flushing as needed, retrograde CTO PCI through severely tortuous epicardial collaterals should be discouraged. Also, soft tip, flexible guidewires with high torque control should be favoured for vessel wiring (e.g. Suoh 0.3),[9] and contrast-guided wiring should be encouraged.

## Vessel perforation

Coronary perforations can be relatively common in CTO PCI,[2] and occur more often when a retrograde approach is employed. Although mostly without serious consequences, they need to be promptly recognized and treated when leading to clinically important scenarios. These include in most patients intramyocardial haematomas, pericardial effusion, and tamponade. Of note, in particular,
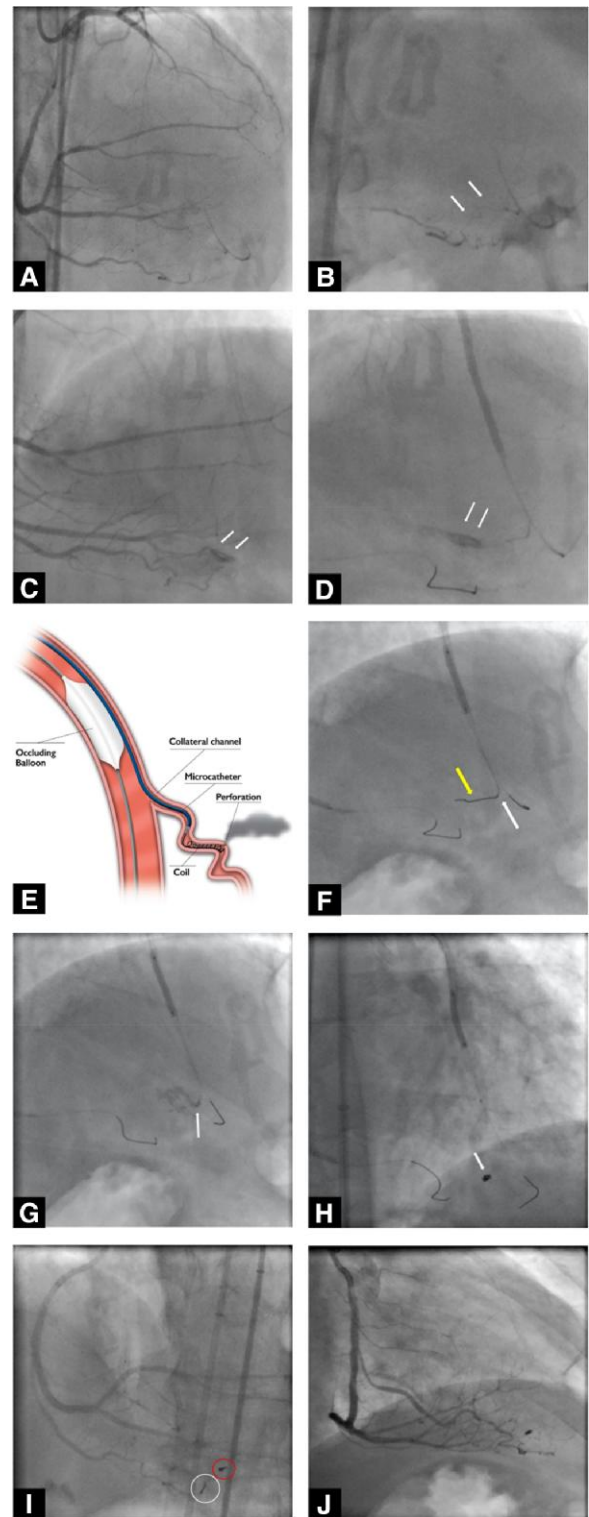


**Figure 4** Epicardial collateral channel perforation treated with simultaneous bilateral coil embolization via the 'block and deliver' technique. Coronary angiography showed mid-LAD CTO filled by epicardial collaterals from an acute marginal (AM) branch of the RCA (*A*). A tip injection through the Finecross microcatheter confirmed the epicardial connection between the distal AM branch and LAD (*B*, arrows). After successful externalization of the retrograde RG3 LAD recanalization was converted to an antegrade fashion. Final angiography showed a large perforation of the epicardial
Continued

**Figure 4** Continued

 collateral channel, that was filled from both sides of the perforation: retrograde contrast extravasation from the distal AM branch of the RCA (*C*, white arrows), antegrade contrast extravasation from distal LAD (*D*, white arrows). The concept of the 'block and deliver' technique: even though the balloon is inflated in parallel to the microcatheter, it is still possible to advance coils in the distal lumen (*E*). Leaving the occlusion balloon inflated into the distal LAD it was possible to negotiate through the jailed Finecross microcatheter (*F*, white arrow: microcatheter tip) the epicardial channel with a Sion Blue guidewire (*F*, yellow arrow: guidewire). A tip injection through the jailed microcatheter confirmed persistent blood extravasation (*G*, white arrow). Successful delivery through the jailed microcatheter of a single 0.010'Axium detachable coil achieved an antegrade hemostasis (*H*, white arrow). Successful delivery of a single 0.010″ Axium detachable coil through the retrograde jailed microcatheter followed (*I*, white circle: coil delivered retrogradely; red circle: coil delivered antegradely). Final angiography showed complete sealing of the perforation (*J*). Re-adapted from *Gasparini GL, et al. Cardiovasc Revasc Med. 2018; 19(7 Pt B):879-886.*

cases generally thought of as protective towards the development of tamponade, such as patients status post coronary artery bypass grafting, loculated effusions may arise, and still yield a clinical picture compatible with tamponade.

In general, this complication is often related to guidewire choice and manipulation, equipment advancement over-the-wire, balloon sizing, and inflation. Although the severity of a perforation definitely matters in terms of management,[10] its anatomical location, i.e. main, distal, or collateral vessel is tightly linked to decision-making. While treatments specifics may differ, the pillars of perforation management are the following:

(1) Balloon inflation, possibly semi-compliant, proximal to the perforation to stop bleeding;
(2) Administration of intravenous fluids, and, if needed, vasopressors;
(3) Recognition of the appropriate timing for pericardiocentesis, considering that smaller effusions may be self-sealing and could be managed conservatively;
(4) Cardiac surgery notification, in case percutaneous management should be unsuccessful.

Of note, the authors believe a reversal of anticoagulation should not be performed until after the removal of intraluminal hardware to avoid the risk of catheter or target vessel thrombosis.

## Main vessel

Main vessel perforation can occur due to high-pressure balloon inflation, balloon rupture, oversized stent implantation (stent/vessel diameter ratio >1), or inadvertent extraluminal wire manipulation followed by equipment advancement within the pericardial space. Indeed, while wire perforation alone (diameter from 0.09 to 0.014″) is unlikely to cause significant blood extravasation into the pericardial space, passage of a larger device, possibly also tearing the vessel wall, is more clinically significant.[11]

### Treatment

First, it is important to note that, if feasible in presence of a proximal main vessel perforation due to balloon rupture, the fastest method to mitigate the amount of pericardial blood spillage is deep engagement of the GC distal to the breach site while preparing and delivering an additional balloon proximal to the perforation site. Thereafter, treatment specifics in case of persistent extravasation after prolonged balloon inflations at the site of perforation include implantation of a covered stent.

If the wire is distal to the lesion and to the perforation site, placement of a covered stent at the level of the perforation should be attempted. In order to minimize bleeding into the pericardial space, delivery of the covered stent could be achieved by:

- Dual ('ping-pong' or duelling) GC technique[12]: while the occluding balloon is inflated proximal to the ruptured vessel wall or crossing over the perforated branch, the GC is withdrawn slightly from the coronary ostia and a second 7 or 8 French GC is advanced up the aorta from an additional femoral access to engage the same coronary ostia alongside the previous GC. A covered stent is then advanced on a wire through the second GC. As soon as it is brought proximal to the occluding balloon, the latter is deflated and withdrawn proximally. Wire and covered stent are then advanced to the perforation site and deployed. Retrieval of occluding balloon, first wire, and first guide follows after evidence of adequate perforation sealing (*Figure 3*).
- Single catheter technique[2]: in presence of an 8 French GC, which can house both occluding balloon and covered stent, a second guidewire can be advanced directly to the tip of the GC. The occluding balloon can then be transiently deflated to allow wire passage, and then reinflated. The occluding balloon, acting as distal anchor, can thus facilitate delivery of the covered stent to the perforation site, and, in case of delivery failure, can be reinflated until other techniques are employed. Removal of first guidewire and occluding balloon should then proceed with covered stent deployment and postdilation.

On the other hand, should a severe main vessel perforation occur during a CTO PCI before lesion crossing, persistent blood extravasation after prolonged balloon inflations should be followed almost always by coil embolization of the main vessel itself unless a recanalization attempt including covered stent implantation seems safe and clinically reasonable.[13]

## Distal vessel

Inadvertent excessive advancement of a guidewire into the distal coronary bed, either during wiring or equipment exchange, is usually the cause of distal vessel perforation. Stiff, tapered, or plastic jacket guidewires are most commonly involved. Whenever in doubt of such a complication, monitoring via sequential haemodynamic parameters, and echocardiograms[14] should be planned, since seepage of blood into the pericardium may be very slow and tamponade may occur even hours after end of procedure.[2]

### Treatment

Management consists of prolonged balloon inflation at the site of perforation, microcatheter advancement, and aspiration to try and collapse the distal vessel walls[15] or, if still unsuccessful, distal embolization.[2] Embolization with coils is the most common, while fat, thrombin,
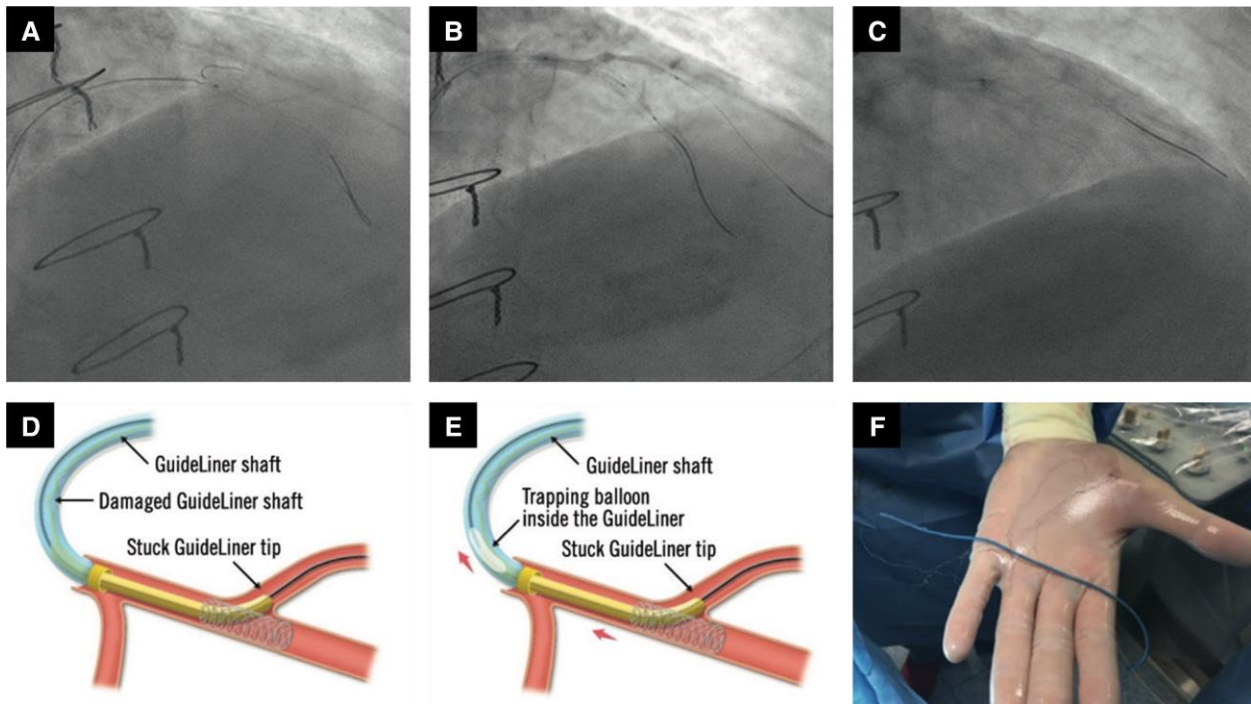
**Figure 5** GC extension entrapment. Wiring of the diagonal branch (*A*). Balloon dilatation of stent struts across diagonal branch (*B*). Entrapment of the GC extension within the stent struts (*C*). Torn and damaged shaft of the guide extension (*D*). Successful retrieval by inflating a balloon into the distal cylinder of the extension device followed by pulling the whole system out as a unit (*E*). Complete retrieval of the entrapped device (*F*). Re-adapted from *Gasparini GL, et al. EuroIntervention. 2021;17(3):212-219.*

thrombus, microparticles, portion of a guidewire, or other materials are less predictable and more technically challenging. This can be achieved via:

- Dual GC technique: similar to that described above for covered stent delivery, this technique requires additional access and GC through which a microcatheter housing the coils to be delivered is inserted distal to the occluding balloon.
- Single GC ('block and deliver') technique (*Figure 4*)[13,16,17]: simultaneous delivery of an occluding balloon and a microcatheter through a single GC is feasible, and coil advancement in the distal lumen is possible even in presence of an inflated balloon on top of the microcatheter. In addition, selective tip injections through the microcatheter allow assessment of hemostasis without the need to repeatedly deflate the occlusive balloon. While the first description of this technique was described using 8 French GC, the more recent Balloon Microcatheter technique can be performed with a single ≥6 French GC, which renders it extremely practical to be performed through the more commonly employed 6 and 7 French GC.

When the perforated branch is too small or too angulated to allow wiring and delivery of a microcatheter, covered stent implantation across the ostium of the perforated branch is the alternative. In case of failure, prolonged balloon inflations may lead to hemostasis, otherwise, cardiac surgery may be required.

## Collateral

Similarly to distal vessel perforation, collateral vessels may be breached during guidewire manipulation and other equipment advancement or exchange, so extreme care should be kept handling guidewires, even if only for support. According to its location, perforation or rupture of a collateral vessel may be of different clinical significance. Indeed, involvement of epicardial collateral is a very serious complication, that can rapidly lead to tamponade and may be quite difficult to treat. Conversely, perforation of a septal branch is unlikely to be associated with severe clinical consequences. Accordingly, treatment of such complications differs.

## Septal collateral

Even though large septal haematomas and even cardiac tamponade secondary to septal collateral rupture are reported,[18] septal perforation is mostly a rare and self-limited event, ending often with drainage in one of the cardiac chambers and negligible clinical consequences.[10] Selection of a thin, tortuous septal channel, aggressive septal crossing, microcatheter advancement manoeuvres, or dilation of the septal channel may all lead to this complication.

## Treatment

Usually, no specific treatment is required. Microcatheter advancement alone may otherwise be frequently enough, while in other cases vacuuming via aspiration from a syringe often leads to vessel wall collapse.[15] If tamponade occurs, the perforated collateral may need to be coiled.

## Epicardial collateral

Epicardial approach should be attempted only by expert operators in CTO and retrograde interventions and as a last resort. The main reason is that epicardial collateral perforation is an extremely dangerous complication that can rapidly lead to tamponade and haemodynamic collapse, irrespective of a previous history of coronary artery bypass grafting. An aggressive guidewire or microcatheter advancement through tortuous collaterals might promote vessel damage. In this setting, it is important to remember to avoid epicardial collateral dilation or surfing, while contrast-guided wiring via tip injections should be performed.

### Treatment

General perforation treatment measures should be employed in case of epicardial collateral perforation. Immediate balloon inflation and negative aspiration from the microcatheter after wedging the tip should be implemented at once.[15] If unsuccessful, distal embolization with coils can be tried. Nonetheless, given the bidirectional blood flow, coil embolization should ideally be performed at both ends of the collateral (*Figure 4*).[11] In presence of a non-recanalized CTO selective retrograde coil embolization could still be adequate for hemostasis, given the often very low distal perfusion pressure beyond an occlusion. Should bilateral angiography confirm otherwise significant bidirectional blood supply, emergent surgical intervention may be required.

## Equipment entrapment or loss

Equipment delivery in CTO PCI can be challenging due to the presence of severely calcified, tortuous vessels, and the need to negotiate very narrow channels. An increased risk of device entrapment derives also from aggressive wiring and ballooning techniques used during CTO PCI, as well as retrograde advancement of equipment through small sharply angulated collateral branches. Overall, it is an infrequent (incidence of 1.5%) but potentially life-threatening complication predisposing patients to an increased risk of vessel perforation, vessel thrombosis, and early and late myocardial infarction.[19]

The occurrence of device (guidewire, microcatheter, GC extension, balloon, rotational atherectomy burr) entrapment can be reduced by avoiding rapid advancement of an excessive force or torque transmission to coronary devices, especially in small, tortuous, and calcified lesions. As a rule of thumb, the number of turns applied to microcatheters should be limited to 10, while clockwise and counterclockwise rotation should be alternated with turns up to 360 degrees when guidewire drilling manoeuvres. In addition, the tip of the antegrade microcatheter, balloon or stent should never be allowed to meet the tip of the retrograde microcatheter over the same guidewire.

### Treatment

Once entrapment has occurred, different techniques are available to address this complication (*Table 1*). Smooth traction should be applied as a first-line strategy in order to free the device. Post-entrapment modification of the plaque might be helpful, whenever possible (e.g. in rotational atherectomy burr entrapment). Likewise, careful tension on the device should be applied by using microcatheters, snares, or telescopic GC extension in order to provide a more focused and coaxial application of the withdrawal force, facilitating the retrieval of the device. Of note, guidewire retrieval attempts may lead to tip coil unravelling into small filaments, and snaring might be then required. Trapping of the device with a balloon close to the GC tip, followed by traction transmitted to the GC itself might be employed as well. In the case of guidewire entrapment, controlled rupture might be considered in some cases. It is important to ensure trapped wires are covered by microcatheters in order to avoid proximal vessel dissection upon traction. Finally, the advancement of several guidewires in parallel to the entrapped one followed by multiple turns to wrap it might sometimes allow its retrieval.[2]

Management of lost equipment should start with a determination of the actual need to retrieve it rather than to deploy or crush it. If device deployment or crushing is selected, intravascular imaging should be employed to ensure adequate coverage. Otherwise, retrieval of lost devices (often stents) can be performed with either a snare or the small balloon technique. If the guidewire position is maintained within the stent upon its loss, a small balloon can be advanced through the stent, inflated distal to the stent, and withdrawn together with the stent within the GC. Overall, successful percutaneous management of device entrapment or loss can usually be achieved (*Figure 5*).

## Conclusions

CTO PCI is among the most complex procedures within the current interventional panorama. As such, the operator should be aware of potential complications and should plan the procedure in order to minimize their risk of occurrence and promptly respond to them if they do arise. Percutaneous treatment of the principal acute cardiac coronary complications, including vessel closure, perforation, and equipment entrapment or loss, is feasible most of the times, and the operator should be aware of the key techniques to successfully bail out.

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## Data availability

No new data were generated or analysed in support of this research.

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