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Conquer coronary artery perforation with magic hands

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ABSTRACT Coronary artery perforation (CAP) poses a significant challenge for interventional cardiologists. Management of CAP depends on the location and severity of the perforation. The conventional method for addressing the perforation of large vessels involves the placement of a covered stent, while the perforation of distal and collateral vessels is typically managed using coils, autologous skin, subcutaneous fat, microspheres, gelatin sponge, thrombin or other substances. However, the above techniques have certain limitations and are not applicable in all scenarios. Our team has developed a range of innovative strategies for effectively managing CAP. This article provides an insightful review of the various tips and tricks for the treatment of CAP.

Coronary artery perforation (CAP), called "the nightmare of cath labs", refers to the contrast or blood leaking out of the vessel through tears of coronary artery. The occurrence of CAP is related to the lesion characteristics and the complexity of percutaneous coronary intervention (PCI). In uncomplicated lesions, the incidence of CAP ranges from 0.2% to 0.4%.[1] Older age, female, previous PCI, multivessel lesions, calcification, small and tortuous arteries, use of oversized balloons/stents, high inflation pressures and rotational atherectomy are considered as the risk factors.[2] CAP is more frequently encountered in chronic total occlusion (CTO) PCI with a general incidence of 4%–9%[3] and up to 15% in cases involving the retrograde approach[4]. Apart from increasing the cost of PCI,[5] CAP can result in serious complications such as cardiac tamponade, hemodynamic collapse and even death.[2]

CLASSIFICATION AND CLINICAL MANIFESTATIONS

According to the location, CAP can be categorized into three types: large vessel perforation, distal vessel perforation and septal/epicardial collateral perforation. Large vessel perforations refer to the tearing of main coronary artery or branch with a diameter of ≥ 2 mm. This type of perforation is often a result of using oversized stents or overinflated balloons, especially in cases of tight and severely calcified lesions. Distal vessel perforations involve the tearing of distal or small coronary artery branch with a diameter < 2 mm, commonly caused by the movement of distal guidewires like polymer-jacketed guidewires.[6] The perforation of septal/epicardial collaterals usually occurs when the retrograde approach is used in CTO PCI.[4]

According to angiographic imaging, Ellis, *et al*.[7] classified CAP into four categories: type I: a crater extending outside the lumen only; type II: pericardial or myocardial blush without a ≥ 1 mm exit hole; type III: frank streaming of contrast through a ≥ 1 mm exit hole; and type III cavity-spilling: perforation into an anatomic cavity chamber. It is important to note that some of these perforations, such as those into the left ventricle, right ventricle, or coronary sinus, do not require treatment.

GENERAL PRINCIPLES

Once CAP is confirmed, it is crucial to take immediate steps to prevent further extension of the perforation (Figure 1). The initial step is to inflate a balloon with a diameter equal to that of the vessel (1:1 ratio) either proximal to or at the site of perforation using a low pressure (≤ 8 atm). In cases involving the large vessels, the duration of complete occlusion by balloon inflation should not exceed over 20 min.[8] If the above method proves ineffective, we can try to reduce the balloon pressure to keep TIMI II flow for a longer period of time. If these measures are unsuccessful, alternative therapies should be attempted. Type III CAP can result in cardiac tamponade

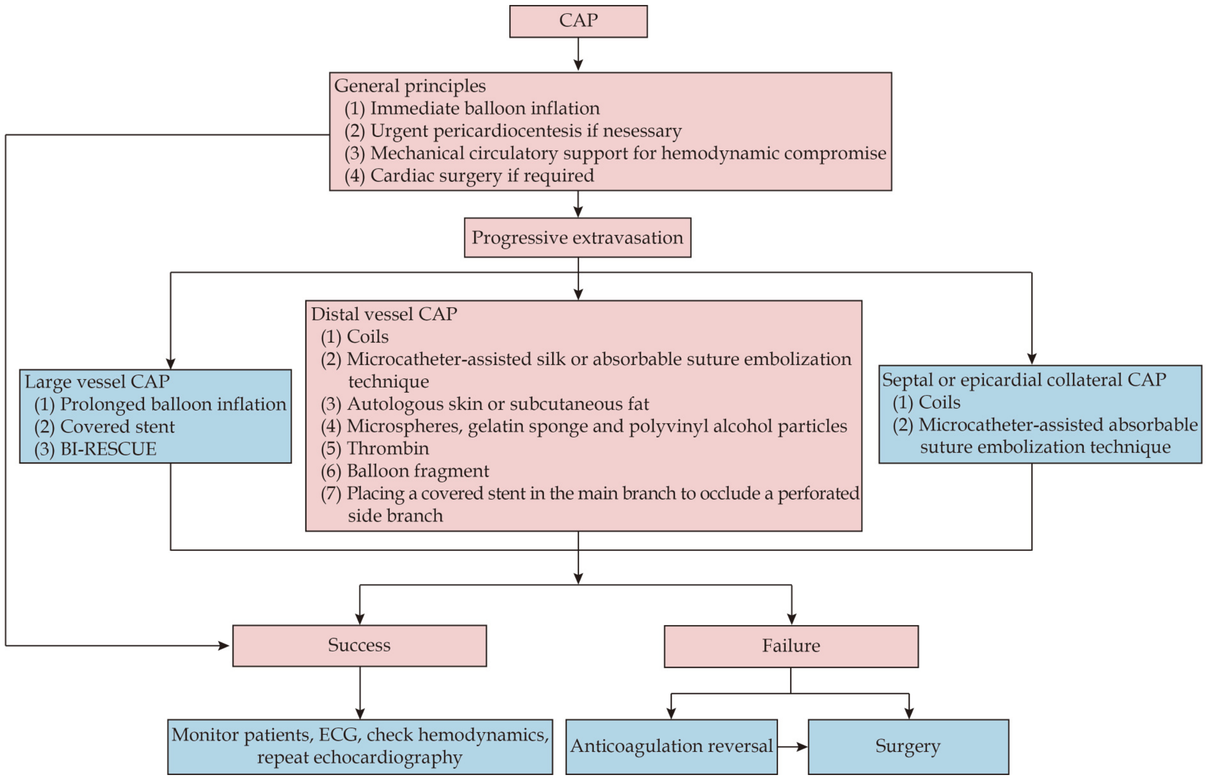

Figure 1 Algorithm for the management of CAP. BI-RESCUE: the balloon occlusion and thrombus aspiration catheter mediated-distal coronary perfusion technique; CAP: coronary artery perforation; ECG: electrocardiogram.

with hemodynamic collapse, with some patients experiencing hemothorax or intramural hematoma.[9,10] Confirmation through X-ray or echocardiography is typically needed, and urgent pericardiocentesis should be performed if necessary.

Hemodynamic stability is extremely important for CAP. In instances of hemodynamic compromise, immediate administration of intravenous infusion, blood transfusion and vasopressor is essential. Mechanical circulatory support options, including intra-aortic balloon pump, Impella, extracorporeal membrane oxygenation and TandemHeart, can be used, and the cardiopulmonary bypass system can also be considered.[11] Reinfusion of pericardial blood through the central vein is another therapeutic option to reduce the need for blood transfusion. However, the reinfused blood is non-filtered and increases the risk of bleeding, disseminated intravascular coagulation and stent thrombosis. In addition, there are potential risks such as infective events and hyperkalemia due to hemolysis, thus the application of this technique should be cautious. Anticoagulation reversal is a potential treatment option for CAP; however, it is better to be considered after all intracoronary devices have been removed to avoid the risk of life-threatening thrombotic complications. In recent years, the use of covered stents and distal embolization techniques has led to a decrease in the use of protamine.

When the patient's condition is unstable, echocardiography should be performed more frequently. Even if the patient's condition is stable, routine echocardiography should be performed 3–8 h after CAP, especially in case of distal CAP. Despite potentially subtle symptoms, delayed pericardial effusion and tamponade may occur within several hours after CAP. If tamponade occurs, prompt pericardiocentesis is needed. Following pericardial drainage of less than 50 mL/24 h, subsequent echocardiography is recommended to rule out the residual effusion before removing the drainage catheter.[12] If pericardiocentesis is not feasible, cardiac surgery may be needed. With a high mortality rate in such cases.

LARGE CAP

Covered Stents

For type I or type II CAP, it may be possible to effectively seal the perforation by extending the occlusion period of the balloon and/or implanting conventional stents.[13] In the case of type III CAP, if the vessels have a diameter ≥ 2.5 mm and lack large branches, the covered stent ought to be implanted at the site of perforation immediately. If a guiding catheter with a diameter of 8F or larger is utilized, the lumen diameter is sufficient to accommodate both the covered stent and the blocking balloon through the same catheter. Alternatively, for 6F or 7F guiding catheters, the "ping-pong technique" can be attempted to advance the second guiding catheter through a new vascular access. The second guidewire is delivered via the second catheter to the proximal segment of the blocking balloon. After brief deflation of the blocking balloon, the second guidewire is pushed to the distal segment of the perforated vessel.[14] The covered stent is then delivered along with the second guidewire to complete the implantation.

A polytetrafluoroethylene (PTFE) stent constructed using a sandwich technique is the most commonly used covered stent. When using a PTFE stent, it is better to choose a 7F guiding catheter given that a 6F guiding catheter can only pass through a stent with a diameter of 2.75–3.5 mm. The deliverability of PTFE stents is inferior compared with drug-eluting stents or bare-metal stents, especially in severely calcified or tortuous vessels. Polyurethanes are known for the good biocompatibility, physicochemical characteristics and mechanical properties. PK Papyrus covered stent is a cobalt-chromium stent covered with polyurethanes polymer. It adopts specialized technology to make polymer thinner and more flexible. The stent comes in sizes ranging from 2.5 mm to 5 mm, which renders it compatible with a 5F or 6F catheter. The pericardium is a collagen-rich tissue with high biocompatibility. Aneu GraftDX is a 316L stainless steel stent covered with equine pericardium, which can be successfully employed in CAP.[15] However, covered stents are not universally available in all catheterization laboratories. Some self-made covered stents can also be developed as a bail-out strategy.[16]

Compared with drug-eluting stents, covered stents exhibit higher rates of restenosis, stent thrombosis and target vessel revascularization.[17] When addressing large bifurcation perforation, the use of covered stents may result in branch occlusion. A stiff wire can be delivered through a double-lumen microcatheter to penetrate the PTFE layer, thereby reopening the side branch. It was reported that the jailed balloon technique or kissing stent technique can be used to prevent branch vessel occlusion.[18,19] Following the implantation of covered stents, intracoronary imaging modalities are helpful to assure adequate stent expansion. Unless there are contraindications, dual antiplatelet therapy should be used for at least 12 months after the successful sealing of the perforation to reduce the risk of late stent thrombosis.

The Balloon Occlusion and Thrombus Aspiration Catheter Mediated-distal Coronary Perfusion Technique (BI-RESCUE)

Initially, balloon inflation serves as the primary treatment for type III CAP in the proximal and middle coronary arteries; however, it often results in myocardial ischemia. Although perfusion balloon catheters have been shown to reduce myocardial ischemia during prolonged balloon inflation, they can only supply 10%–15% of coronary blood flow. To address this issue, Gong, *et al.*[20] invented the BI-RESCUE technique for treating the large vessel perforation. With this technique, the CAP can be blocked by long-term inflation of the balloon, and the perfusion of the distal vessels is similar to physiological state. BI-RESCUE technique is illustrated in Figure 2.

Immediately after the occurrence of large coronary artery perforation, a blocking balloon should be swiftly delivered to the perforation site and inflated at a lower pressure (8-10 atm) to prevent continuous bleeding. Then, another guiding catheter should be engaged (ping-pong technique) and a guidewire should be delivered to the distal segment of the perforated vessel. A thrombus aspiration catheter is advanced over the guidewire to the distal segment of the perforated vessel. Once the perforation is sealed by the inflated balloon, blood is drawn from the first guiding catheter and injected into the distal segment of the perforated vessel via the aspiration catheter to maintain the distal perfusion, subsequently avoiding myocardial ischemia and increasing the chance of a successful closure of the perforation.

There are several tips when using this technique. Firstly, the ping-pong technique should be utilized to deliver another guidewire and the thrombus aspiration catheter. Secondly, the blocking balloon should be precisely located at the perforation site rather than the proximal part to the perforation, otherwise bleeding may not be ceased when the distal vessel is perfused through the aspiration catheter. Furthermore, to confirm the perforation closure by the blocking balloon, contrast should be injected through the aspiration catheter before autolog-

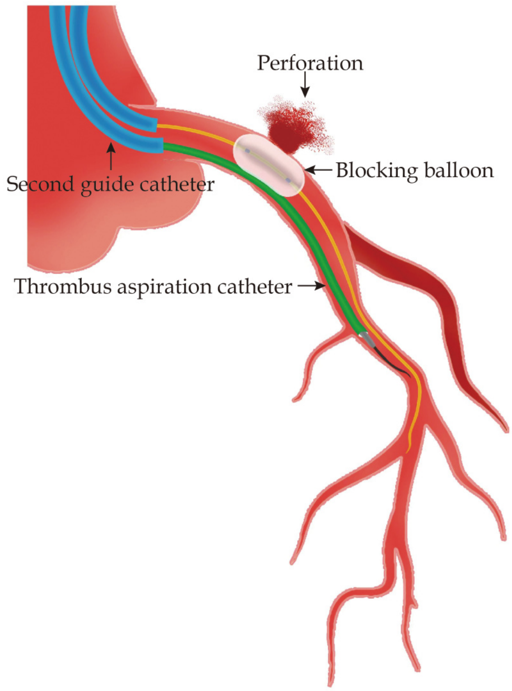

Figure 2 Illustration of the BI-RESCUE technique. BI-RESCUE: the balloon occlusion and thrombus aspiration catheter mediated-distal coronary perfusion technique.

ous blood injection. If the perforation is not entirely closed, it is recommended to adjust the position and/or pressure of the blocking balloon. Thirdly, the thrombus aspiration catheter should be used to maintain distal perfusion instead of microcatheter for the consideration of lumen size. *In vitro* experiments demonstrate that the average maximum blood flow per minute via the thrombus aspiration catheter significantly surpasses that of the microcatheter (Table 1). In addition, once the thrombosis occurs, it can be removed by the thrombus aspiration catheter. The technique is effective, convenient, inexpensive and widely available. We believe the BI-RESCUE technique could be an effective alternative to the covered stents, and this technique has the potential to be the first option in some large vessel perforations by well experienced operators.

DISTAL CAP

Perforation of distal coronary artery may lead to cardiac tamponade. Usually a microcatheter can be delivered at the perforation site to apply suction and collapse the distal vessel wall to stop bleeding.[21] If this method proves ineffective, distal embolization should be done immediately. Coil, subcutaneous fat, autologous skin, autologous blood clots, thrombin, microspheres, collagen, gelatin sponge, polyvinyl alcohol particles, balloon fragments or the tip of wires may be used for distal embolization.[22–24] Commonly used delivery devices include thrombus aspiration catheters, over-the-wire (OTW) balloons or microcatheters. Microcatheters and OTW balloons are recommended to deliver embolic substances for more precise placement.

Coils

Coils, covered with synthetic wool or Dacron fibers, are inert metal devices known to promote thrombosis. In cases of distal CAP, where prolonged balloon inflation proves ineffective, 0.014- and 0.018-inch coils are commonly used to seal the perforation. The 0.014-inch coils are favored for their compatibility with any microcatheters, while the 0.018-inch coils require a microcatheter with a larger inner diameter, such as Progreat and Finecross. Moreover, coils can be classified as pushable or detachable by delivery mechanism. Pushable coils can be advanced and deployed at the targeted area using a guidewire or a dedicated wire, whereas detachable coils are typically attached to a wire that facilitates delivery to the target area. If the deployed position is unsatisfactory, the coil can be retracted and repositioned. If the position is appropriate in the perforation vessel, the detachable coil can be separated from the delivery catheter using one of three mechanisms: electric, mechanical, or hydraulic detachment.[25] However, the use of coil increases the cost, which limits its widespread use.

Autologous Skin or Subcutaneous Fat

After routine disinfection, a small amount of skin can be excised from the puncture point. It is suggested that the size of the skin should be determined according to the size of the target vessel and the perforation. The skin is then punctured with the end of the guidewire and delivered to the proximal segment of the perforation using

Table 1 Maximum volume of blood flow per minute between microcatheters and thrombus aspiration catheters.

	Microcatheters, mL		Thrombus aspiration catheters, mL		
	Finecross	Corsair	ASAP-LP	Thrombuster II	Export
Maximum volume of blood flow per minute	8	2	70	120	99

a balloon.[26] Subcutaneous fat tissue embolization could also be used to treat distal CAP. Once the location of the perforation is confirmed, a microcatheter or an OTW balloon is delivered to the proximal segment of the CAP along the guidewire. A small piece of subcutaneous fat (≤ 3 mm in diameter) excised from the puncture point is sliced into small particles (0.5–1.0 mm in diameter), which are slowly pushed through the microcatheter or OTW balloon by injecting the diluted contrast.[27] The advantage of using autologous skin or subcutaneous fat lies in its availability, and absence of the need for protamine to neutralize heparin. However, there are some potential risks in this method. Leakage of subcutaneous tissue into any of the three main coronary arteries may lead to acute myocardial infarction. Therefore, the tip of the microcatheter or OTW balloon should be positioned at the perforation site as accurately as possible.

Microspheres, Gelatin Sponge or Polyvinyl Alcohol Particles

Microspheres are non-absorbable, spherical and hydrophilic particles with sizes ranging from 1 μm to 1500 μm. When encountering distal CAP, microspheres can be delivered through a microcatheter to seal the perforation. However, there remains a lack of evidence supporting the safety and effectiveness of this treatment.[28] Gelatin sponge, when cut into small particles and mixed with diluted contrast, can also be injected into the perforation site through a microcatheter. It can be degraded and absorbed after 90 days, but may cause inflammation, granulomatous vasculitis, no-reflow, slow flow or other adverse reactions.[29] It is also possible to seal the distal CAP by injecting polyvinyl alcohol particles through either an OTW balloon or a microcatheter.[30] The application of microspheres, gelatin sponge or polyvinyl alcohol particles may flow back into other coronary arteries, leading to the unpredictable vascular occlusion. Therefore, a proximal balloon needs to be inflated for several minutes to prevent that from happening.

Thrombin

Thrombin is a highly specific serine proteolytic enzyme, which is dissolved in saline to achieve a desired concentration of 100 IU/mL. The thrombin solution is injected slowly (over 5 min) through either a microcatheter or an OTW balloon using a syringe.[31] It is recommend to inflate a proximal balloon before the thrombin injection to prevent its flow back into other coronary arteries.

Balloon Fragment

Operators can cut a balloon in the middle, thread the distal segment of the balloon fragment on the guidewire, and then use a second balloon to push it forward to the proximal site of the perforation. Following that, the guidewire is gently pulled back, leaving the balloon fragments in the perforation site. Multiple balloon fragments can be used until the bleeding is completely stopped.[32]

Microcatheter-assisted Silk or Absorbable Suture Embolization

In the process of CTO PCI, the occurrence of distal CAP is increasing due to the use of more penetrating guidewires. Li, *et al.*[33] and Sheng, *et al.*[34] invented a technique to treat distal CAP and septal/epicardial collateral perforation using silk or absorbable suture embolization via the Finecross microcatheter. The advantages of the technique include effectiveness, low cost, easy operation and availability in all catheterization laboratories.

Illustration of the microcatheter-assisted silk or absorbable suture embolization is depicted in Figure 3. After the occurrence of distal perforation (Figure 3A), a guidewire is delivered to the perforation site (Figure 3B). A microcatheter (Finecross is preferred) is advanced to the proximal segment of the perforation along the guidewire (Figure 3C). The inner diameter of Finecross microcatheter is 0.4572 mm (0.018-inch coils), and its inner cavity is coated with PTFE, suitable for delivering a 3–0 silk or absorbable suture. Then the guidewire is withdrawn (Figure 3D). The tail of the microcatheter should be filled with heparin saline (Figure 3E). The 3-0 silk or absorbable suture (8–10 mm) is prepared (sharp scissors or a blade is used to cut the silk suture to have a clear end which makes it easy to push), and vertically positioned to the tail of the microcatheter (Figure 3F). The silk suture should be gently pushed into the non-radiopaque portion of the microcatheter by an introducer (Figure 3G), while the absorbable suture automatically sinks into the same place. Then the guidewire is inserted to slowly push the suture (Figure 3H). During the pushing process, the guidewire can be slightly pulled out and pushed again once the resistance is encountered. The position of the microcatheter should be confirmed under fluoroscopy when the guidewire is close to the tip of microcatheter. When the suture is pushed out of the mi-

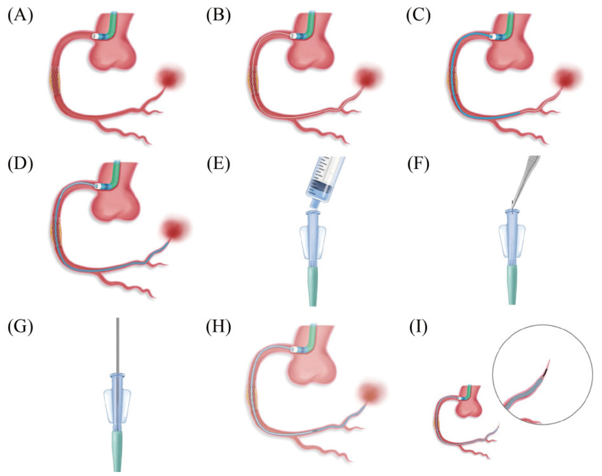

Figure 3 Illustration of the microcatheter-assisted silk or absorbable suture embolization technique. (A): Distal perforation; (B): deliver a guidewire to the perforation; (C): advance a microcatheter proximally to the perforation; (D): withdraw the guidewire; (E): fill the microcatheter tail with heparin saline; (F): prepare and place a 3–0 silk or absorbable suture into the microcatheter tail; (G): push the silk suture into the microcatheter using an introducer; (H): further push the silk or absorbable suture using a workhorse guidewire; and (I): the silk or absorbable suture at the perforation.

crocatheter to the perforation site (Figure 3I), coronary angiography should be performed to observe whether the perforation is successfully blocked. If necessary, the above steps could be repeated for several times until the perforation is blocked.

SEPTAL OR EPICARDIAL COLLATERAL PERFORATION

The retrograde approach for CTO is associated with more complex anatomy.[35] During CTO PCI using the retrograde approach, there is a risk of perforating collateral vessels when advancing guidewires or other devices. Although ventricular septal hematoma and cardiac tamponade due to the septal perforation have been reported, most septal collateral perforations are self-limiting and unlikely to result in severe clinical consequences. In contrast, perforation of epicardial collaterals can lead to cardiac tamponade and hemodynamic failure rapidly. Even pericardial adhesion from a previous coronary artery bypass grafting may not prevent pericardial tamponade, as bleeding can form a loculated hematoma to compress the cardiac chamber, leading to hypotension, shock and even death.

Early identification of the perforation is crucial during CTO PCI. When CTO is performed through septal or epicardial collaterals, angiography should be performed before and after withdrawing the microcatheter to check for perforation. Immediate action, such as balloon dilatation and microcatheter aspiration,[36] should be taken if perforation is detected. If these measures are unsuccessful, it is recommended to seal both ends of the collateral perforation with coils or absorbable sutures. However, many catheterization laboratories still lack the availability and expertise for using coils. Although thrombus, subcutaneous fat[27] and thrombin[37] have been used, each of above techniques has its limitations. We believe that absorbable suture embolization may be an optimal technique for this scenario due to its universal availability. There are several tips when using this technique. In cases of bilateral bleeding from collateral perforation after recanalizing CTO, microcatheters should be advanced along the externalized wires from both antegrade and retrograde directions, followed by bilateral embolization. Generally, 3–0 absorbable suture is recommended. Compared with the silk suture, the smooth surface of the absorbable suture reduces the risk of entrapment during the pushing process through tortuous collaterals.

CONCLUSIONS

As a severe complication of PCI, CAP should draw the attention of interventional cardiologists. Once CAP occurs, it should be identified as early as possible. This article presents a summary of contemporary treatment techniques to provide help for better managing the CAP. Our team has invented the BI-RESCUE technique and the microcatheter-assisted silk or absorbable suture embolization technique, which were proved to be effective, safe and readily accessible for the treatment of CAP.

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