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Review

Algorithm for Cardiac Vessel Perforation: State of the Art

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Abstract

Background: Coronary artery perforation is a potentially life-threatening complication in 0.2–0.6% of all patients undergoing percutaneous coronary intervention. Despite the ongoing development of technical skills and coronary devices, severe recalcitrant calcified coronary lesions remain a challenge for interventional cardiologists and can carry a potential risk for life-threatening complications, including coronary perforation. Discussion and Conclusion: The algorithm for cardiac vessel perforation could be more comprehensive and cover preventive and predictive measures. It is necessary to take into consideration prompt recognition, implement actions to restabilize the hemodynamic status, understand the source and mechanism of bleeding, and classify the cause of bleeding into proximal, distal, coronary artery bypass graft and collateral vessel, pericardial, myocardial extravasation, and vessel-chamber perforation, as each causality would necessitate a different management strategy for a successful outcome. Imaging information about cardiac vessel injury is useful for a better understanding of the spatial orientation of the coronary vessels. It also helps to detect a hematoma that deteriorates the hemodynamic status without effusion "dry tamponade" and could have a particular role in cardiac interventions to predict and prevent this complication.

Keywords: coronary perforation; great cardiac vein; calcific lesion; pericardial effusion; cardiac computed tomography; covered stent

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1. Introduction

Coronary artery perforation (CAP) is a potentially life-threatening complication in 0.2–0.6% of all patients undergoing percutaneous coronary intervention (PCI) [1]. The incidence rate increases in complex PCI, such as chronic total occlusion (CTO) PCI (4%) [2]. CAP is associated with early and late major adverse cardiac events, such as cardiac tamponade, hemodynamic compromise, and death [2]. There is also a legacy effect, in which an increased risk of adverse outcomes persists into the chronic phase despite the resolution of the acute CAP event [3].

CAP occurs as an anatomical breach in the integrity of the coronary vessel wall by penetration from inadvertent guidewire exit, especially when polymer-jacketed guidewires

are used [4,5]. It can also be caused by highly calcified stenotic lesions that are not properly remodeled by de-bulking devices upfront, as well as excessive de-bulking with plaque modification during PCI with intimal tear due to oversized and/or high inflation pressures of balloons, stents, cutting and scoring balloon, balloon rupture "grenadoplasty", or dissection that propagates outward [6].

In addition, coronary atherectomy de-bulking devices (e.g., rotational, orbital and/or laser atherectomy, and shockwave lithotripsy) can breach the integrity of the coronary vessel during aggressive plaque modification and extravasation, and cause hematoma injury to neighboring cardiac structures [1]. It could lead to extravasation of blood into the myocardium, causing hematoma and intramural ischemia, into the pericardium, causing dry hematoma or pericardial effusion, or into the cardiac chamber, causing coronary steal phenomenon and angina pectoris. Moreover, mechanical compression or plaque protrusion outside the vessel border leads to injury of the neighboring adherent structures. On the other hand, incomplete breach of vessel integrity leads to intimal tear, dissections, intramural hematoma, plaque rupture, and even total vessel occlusion [6].

Despite the improved success of PCI through the ongoing development of technical skills, coronary guidewires, percutaneous balloons, adjunctive de-bulking devices, and increasing operator experience, severe recalcitrant calcified coronary lesions remain a challenge for interventional cardiologists. Sometimes, the lesions are not amenable to the conventional technique and can carry potential risk for life-threatening complications, including equipment loss/entrapment or coronary perforation. The clinical presentation could be asymptomatic and self-limiting or a deteriorating hemodynamic rash causing cardiac tamponade and acute myocardial infarction. We noticed that most coronary perforation algorithms focused on proximal, distal, and collateral arterial injury and summarized how to deal with this complication, if it happened. However, cardiac vein injury and extravasation of blood into the myocardium, pericardium, or cardiac chamber and their clinical consequences are not comprehensively discussed.

In this article, we tried to improve the coronary perforation algorithm so that it becomes more comprehensive and covers preventive measures, prediction, prompt recognition, understanding of the injury mechanism and the source of bleeding, implementation of therapy to restabilize the hemodynamic status, and sealing of the perforation according to the cause for a successful outcome (Figure 1). Furthermore, we classified coronary vessel perforation into five categories and provided a simplified universal and type-specific approach to manage CAP.

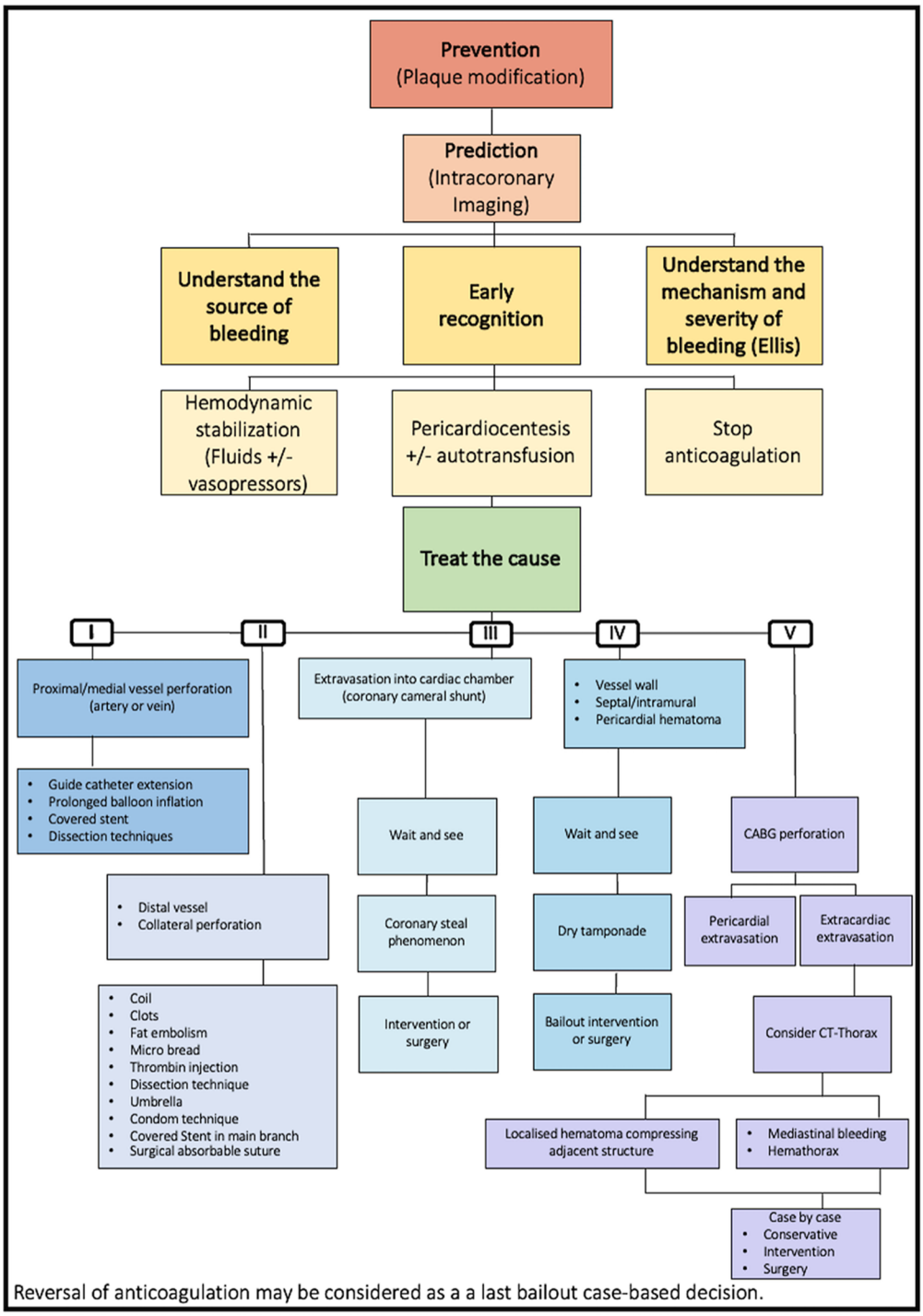


Figure 1. (Central illustration): The cardiac vessel perforation algorithm begins with preventive and predictive measures, goes through understanding the source and mechanism of bleeding, and finally classifies the cause of bleeding into vessel, pericardial, myocardial, and chamber perforation, as each causality necessitates a different management strategy to improve outcomes.

2. Cardiac Vessel Perforation's Algorithm "State of the Art" (Figure 1)

2.1. Prevention

The perforation algorithm should start with preventive measures, as some complications can be prevented, and prevention is the best therapy.

These include gentle handling of equipment, meticulous attention to guidewire position, careful and appropriate sizing of the balloon or stent prior to inflation, avoiding overdilation or high-pressure inflation exceeding the balloon's burst pressure, angiographic

shots to control the results, operator experience, and working against resistance, which are basic technical skills to avoid vessel injury.

2.2. Prediction

Some lesions are not amenable to the conventional technique and can carry a potential risk of life-threatening complications, including equipment loss/entrapment or coronary perforation. Thus, the second step is to be aware of the predictors of coronary vessel injury and perforation.

Extra care measures must be taken for high-risk angiographic predictors (e.g., type B or C lesions, calcified, angulated, tortuous vessels, bifurcation lesions, or chronic total occlusion) to avoid coronary perforation. It is important to be aware of the peculiarity and uniqueness of each coronary vessel. For example, the great cardiac vein courses superficial to the circumflex and LAD arteries in 60–70% of the population and passes under the artery in 30% of the population. An injury of the great cardiac vein after the PCI of a severely calcified Cx lesion has been reported [7]. This is a peculiarity of the Cx compared with other coronary arteries [8]. Prediction of this complication could help with the management strategy and outcomes.

In addition, in a multicenter chronic total occlusion (CTO) PCI registry, the PCI of Cx CTOs was associated with a lower rate of procedural success, lower efficiency, and no significant trend for higher rates of complications [9]. Prompt plaque modifications, using semi-, non-compliant, and high-pressure balloon as well as coronary atherectomy de-bulking devices (e.g., rotational, orbital, and/or laser atherectomy, and shockwave lithotripsy), even in the subintimal space as a bailout strategy (with the exception of rotational, orbital, and/or laser atherectomy), may prevent the breach of the integrity of the coronary vessel. Therefore, perforation can be prevented.

2.3. Early Recognition by Understanding the Mechanism and the Source of Bleeding

The third step provides highlights for early recognition, identification of the exact source of bleeding, and understanding of its mechanism and cause. This is challenging, as a specific inventory is necessary to resolve the underlying pathology and is key to improving outcomes. In the above-mentioned example of great cardiac vein injury, the source of bleeding is not obvious in the coronary angiography unless the operator takes a long cine image and waits for the venous blood to return into the coronary sinus. Thus, it can rapidly deteriorate the hemodynamics and mask the situation with false impressions that there is no source of bleeding or obvious pathology.

Consequently, it could necessitate emergency explorative surgery or bailout intervention to seal the injured vein, which is the most appropriate step to prevent ongoing blood loss.

Only pericardiocentesis or implantation of a covered stent in the Cx artery would not be helpful in this scenario.

2.4. Hemodynamic Stabilization

The fourth step focused on the management of symptoms and hemodynamics. Sedation, intravenous fluids, vasoactive amines, and administration of packed red blood cells or even auto-transfusion if marked blood loss occurs, are basic supportive measures.

Reversal of anticoagulation is not routinely indicated and can be performed after retrieval of the interventional equipment.

Sawayama et al. assessed the impact of heparin reversal while an intracoronary artery device was in place for CAP. Although heparin reversal was associated with successful hemostasis, coronary thrombosis occurred in 7.6% [10].

Therefore, heparin reversal should be performed with caution as a last bailout strategy if other CAP management strategies are exhausted with persistent extravasation, as a case-based decision.

Heparin reversal may precipitate life-threatening complications such as clotting of the pericardial fluid, making it difficult to drain [11], and may lead to impairment of myocardial contractility [12–14].

If the patient develops cardiac tamponade, subsequent pericardiocentesis is essential.

Cardiac tamponade complicating nonelective interventions carries a significantly greater risk of death than tamponade complicating elective interventions, including the possibility of increased late mortality [15].

2.5. Classification of Cardiac Vessel Injury

The fifth step classifies cardiac vessel injury into five categories. The first category is proximal or medial medium-sized vessel injury. This can be an artery or a vein. The second one is a distal and small-sized vessel injury, like collaterals. The third one is the extravasation of blood into the myocardial chamber, causing the coronary steal phenomenon and ischemia beyond the perforation site.

The fourth one is a perforation that leaks blood into the myocardium, causing septal, intramural hematomas, or into the pericardium, causing pericardial hematoma. The fifth category is the perforation of the coronary vessel bypass graft that leaks into the pericardium or extracardiac mediastinal cavity.

Every category has a different causal mechanism and subsequently differs in management.

2.5.1. Category I: Proximal or Medial Medium-Sized Vessel Perforation

The first category to discuss is the proximal or medial medium-sized vessel perforation, including an artery or vein. Should a significant perforation occur, the first step is to prevent continued blood loss. This is usually achieved by prolonged balloon inflation for 10–15 min (1:1 sizing and no more than 8–10 atm) in the proximal portion of the leaking vessel to ensure occlusion of antegrade flow. Hemostasis should be confirmed using contrast injection. In some cases, this may be sufficient to achieve sealing of the perforation (Figure 2).

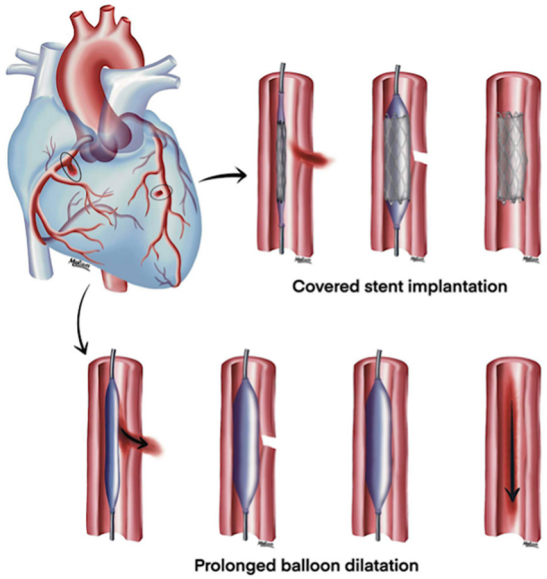


Figure 2. Proximal or medial medium-sized vessel perforation (artery or vein).

Depending on the size of the guide catheter being used and the size of the covered stent, delivery of the covered stent could be achieved using (1) a single guide catheter (also

called "block and deliver" technique) or (2) two guide catheters (dual guide catheter, also called the "ping pong" guide catheter, or the "dueling" guide catheter technique) [16].

Generally, another guide catheter should be considered if the guide catheter used is not 7 French, as additional bulky equipment is likely to be needed.

The second access can be used to introduce a second guide catheter with specific hardware to treat the perforation if needed and to proceed further with the intervention while maintaining hemostasis and minimizing extravasation at the site of perforation with an inflated balloon through the first guide catheter.

If coronary artery perforation persists despite prolonged balloon inflation, a covered stent can be used, especially for perforation at the proximal or mid-segment of the involved artery with poly-tetrafluorethylene (PTFE) and pericardium (Figure 2), such as the Graft-master Rx (8F) (which consists of two bare metal stents with a PTFE sandwiched in-between and is associated with high rates of in-stent restenosis and stent thrombosis), PK Papyrus (6F) ((Biotronik, Lake Oswego, Oregon)) and Begraft covered stent (Bentley InnoMed GmbH, Hechingen, Germany), which is compatible with a 5 French guide catheter [17,18].

Covered stents are generally bulky and require guide-catheter support and possibly other maneuvers, such as a distal anchor balloon for delivery. After deployment, it should be post-dilated to achieve good expansion and reduce the long-term risk of thrombosis. If there are residual dissections beside the covered stents, they should be sealed by additional stenting, as a residual dissection can be a re-entry point for bleeding.

In addition, guide catheter extension can be newly used to temporarily seal the perforation site without prolonged balloon inflation (Figure 3), allowing the intervention to proceed without interruption [19].

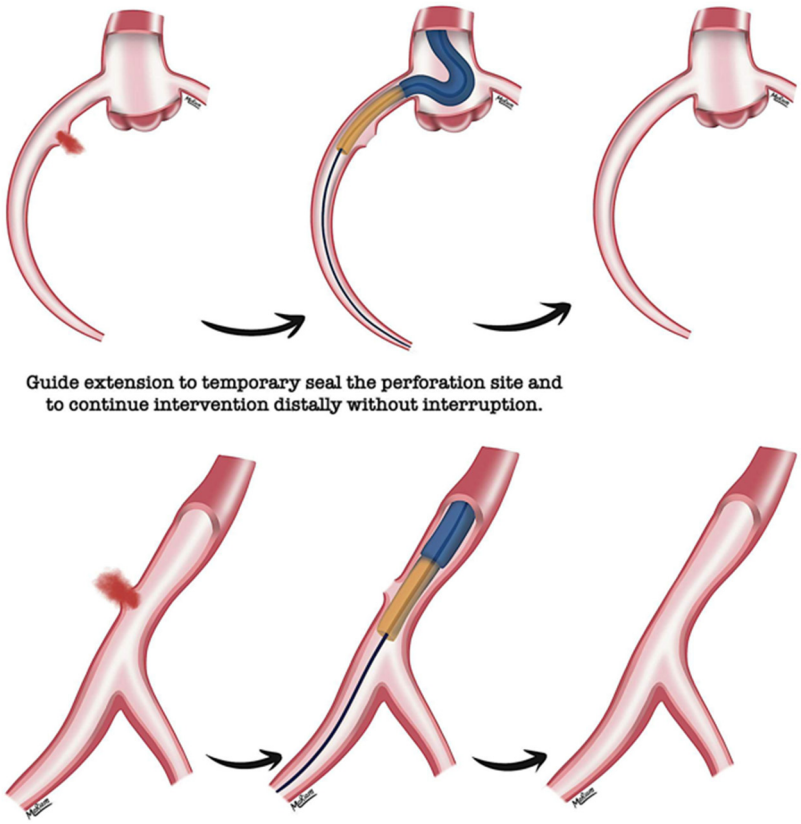


Figure 3. Guide catheter extension technique to temporarily seal the perforation site.

As a bailout, dissection techniques can be an alternative treatment strategy for medium and small distal vessel perforation to create a subintimal dissection membrane that can help seal the perforation (Figure 4).

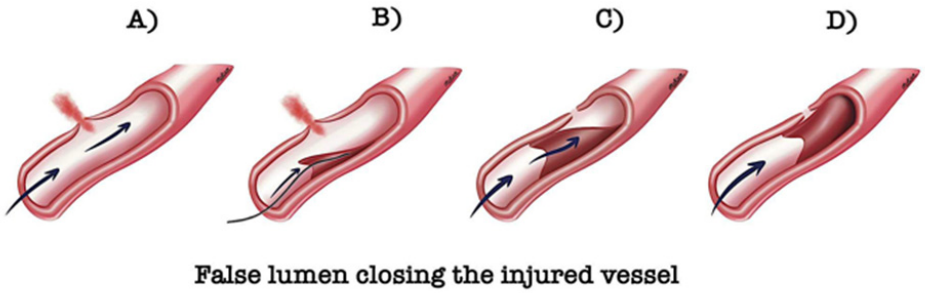


Figure 4. (**A**) medium and small distal vessel perforation, (**B**) the workhorse wire create a subintimal dissection membrane, (**C**) Blood accumulate in the false lumen, (**D**) true lumen compressed and occluded by false lumen.

2.5.2. Category II: Distal and Small-Sized Vessel Perforation, Like Collaterals

It is difficult to diagnose distal and small-sized vessel perforation, especially when collimation is used to minimize radiation exposure, as blood flow into the pericardium may be slow and cause tamponade several hours after the procedure.

This type of perforation is caused by the inadvertent advancement of a guidewire, balloon, or microcatheter into a distal small branch and/or distal wire migration, especially when stiff or polymer-jacketed guidewires are used. In one registry, approximately 90% of distal wire-induced CAP was due to the polymer-jacketed wire family [4,5].

Measures to prevent distal vessel perforation could include paying meticulous attention to the distal guidewire position during attempts to deliver equipment, using the trapping technique to minimize guidewire movement during equipment exchanges, and promptly exchanging a stiff or polymer-jacketed guidewire for a workhorse guidewire immediately after confirmation of successful crossing.

Treatment could be achieved by immediate balloon inflation proximal to the perforation until the preparation of a specific treatment.

Potential specific solutions to seal distal or small-sized vessel perforation include injecting autologous fat through a microcatheter, coils, clots, micro-beads, or thrombin [17] (Figure 5). Embolization can, in most cases, be achieved through a microcatheter and a single guide catheter using the "block and deliver" technique [20]. In addition, an absorbable surgical suture (usually 3.0 absorbable sutures) can be inserted through the microcatheter and pushed distally using a guidewire introducer to seal the distal or small-sized vessel perforation. This suture cannot be seen on fluoroscopy, and its advantage is complete absorption [21].

Furthermore, a novel umbrella-shaped balloon technique (Figure 6) can obstruct the distal small-sized vessel effectively.

The umbrella-shaped balloon fragment is pushed distally with another uninflated balloon. Subsequently, this uninflated balloon and the guidewire are withdrawn to leave the 'umbrella' in place, thus obstructing blood flow to the distal perforation site.

This technique is quick and easy to perform with the use of available tools in the catheter laboratory. However, it carries the risk of creating a new area of myocardial necrosis, which supplies an area with poor collateral circulation [22].

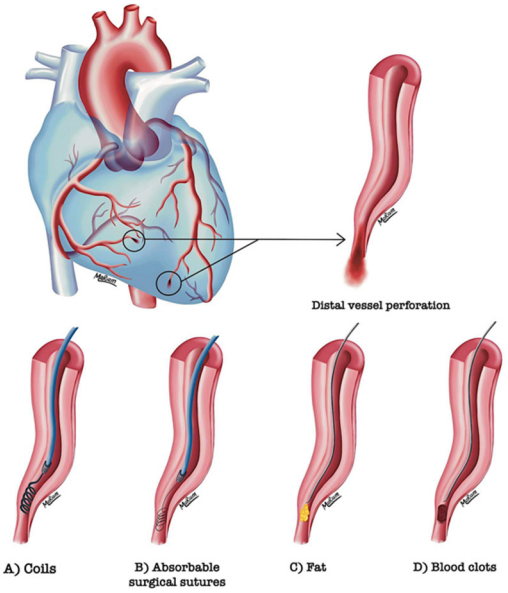


Figure 5. Potential specific solutions to seal distal or small-sized vessel perforation include injecting autologous fat through a microcatheter, coils, absorbable surgical suture, fat, clots, microbeads, or thrombin.

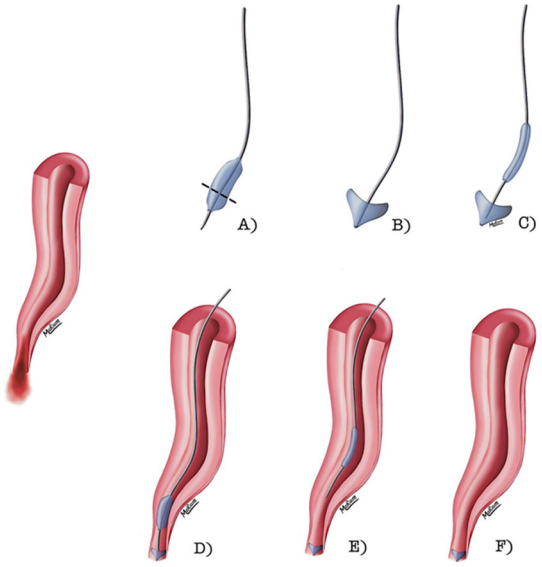


Figure 6. A novel new umbrella-shaped balloon technique can obstruct the distal small-sized vessels effectively. (**A**) cut of the of the balloon, (**B**) at the distal third or half, (**C**) the umbrella-shaped balloon fragment, (**D**) is pushed distally with another, uninflated, balloon, (**E**) the uninflated balloon and the guidewire are withdrawn to leave the 'umbrella' in place, (**F**) obstructing blood flow to the distal perforation site.

A modification of the umbrella-shaped balloon technique is the condom technique, which is an available, adaptable, and easy-to-use interventional tool to obtain distal vascular sealing. It is described as follows:

A cut remnant of the distal part of an angioplasty balloon is mounted on a stent and then pushed over the wire into the target vessel proximally to the distal perforation and implanted, held in place with stent implantation. The wire and the stent delivery system are retracted, leaving the cut remnant balloon in place, and the angiographic control can confirm the complete sealing of the distal vessel flow [23].

Collateral perforations can be technically managed as distal perforations with considerations.

First, septal collateral perforations are usually managed conservatively. However, they can lead to septal, right and/or left ventricular wall hematomas, hemodynamic deterioration, and even "dry tamponade".

Second, epicardial collateral branch perforation is a serious complication of retrograde CTO PCI. It can bleed progressively and may be difficult to control, thus rapidly leading to tamponade [24,25].

In addition, management of significant septal or pericardial collateral bleeding can be challenging because of the dual source of blood supply; therefore, embolization from both antegrade and retrograde feeding vessels to adequately block the source of bleeding from both ends of the collateral would be necessary [24].

If all percutaneous management strategies fail, even the dissection technique, notifying cardiac surgery, would be imperative to expedite management [26].

2.5.3. Category III: Coronary Vessel Perforation with Extravasation into the Cardiac Chamber

The third category could cause specific perforation scenarios with extravasation into a cardiac chamber (Figure 7); these events are almost always benign and self-limiting. However, the coronary steal phenomenon could cause ischemia beyond the perforation site, limit the quality of life, and necessitate a case-by-case decision for percutaneous or surgical intervention [27].

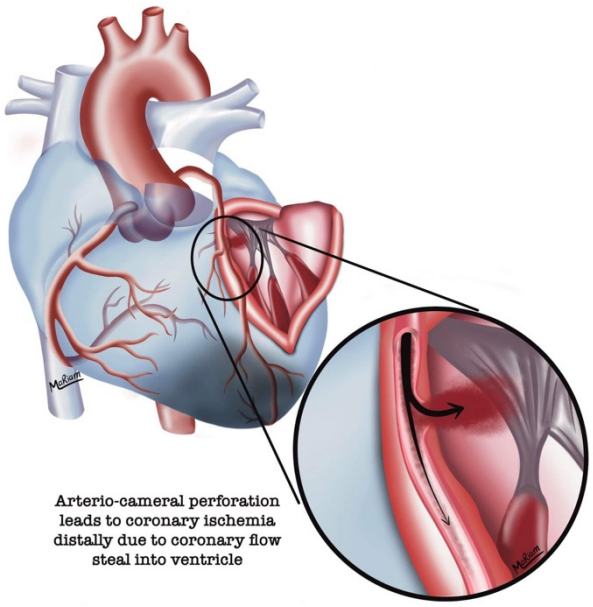


Figure 7. Arterio-cameral perforation leads to coronary ischemia distal to the perforation site due to coronary flow steal into the ventricle.

2.5.4. Category IV: Coronary Vessel Perforation with Leaks into the Myocardium or Pericardium Causing Hematomas

The fourth category could occur if perforation leaks blood into the myocardium, causing large septal, intramural hematomas (Figure 8A), or into the pericardium, causing pericardial hematoma "dry tamponade" (Figure 8B). This may lead to intra-myocardial ischemia and inability of the heart to fill correctly due to the mechanical compression of the adjacent neighboring structures (e.g., pulmonary artery, left atrial inflow and outflow obstruction, and LAD) [12–14,28]. This category has challenges and difficulties in diagnosing and managing the cardiac wall hematoma, as this hematoma can deteriorate the hemodynamic status without effusion "dry tamponade".

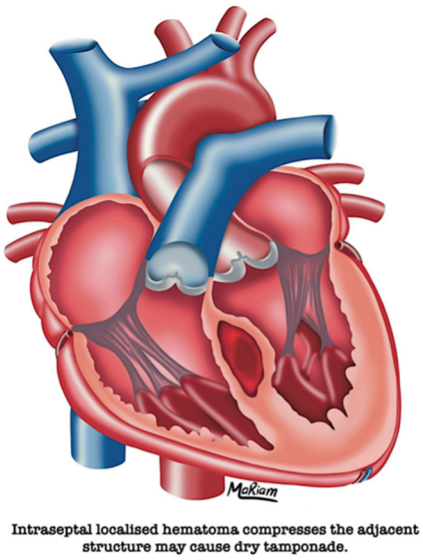


Figure 8. (**A**): Perforation leaks blood into the myocardium, causing large septal intramural hematomas "dry tamponade". (**B**): Perforation leaks blood into the pericardium, causing pericardial hematoma "dry tamponade".

A large hematoma can expand by a self-propagating mechanism as follows:

Avulsed capillary vessels provide active bleeding that fuels their expansion, causing a tear to the epicardium and forming a blood pocket with a tear.

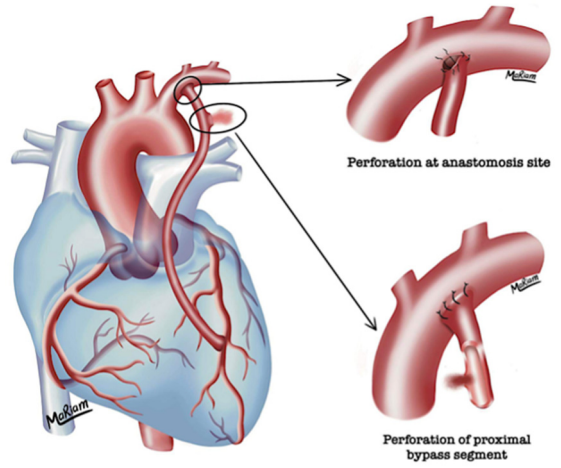
Thus, it can rapidly deteriorate the hemodynamics, mask the situation with false impressions that there is no source of bleeding or obvious pathology, and may require emergency explorative surgery or bailout intervention [12,28,29].

Surgical closure of the blood pocket could be managed using a polypropylene suture, leaning on strips of polyethylene terephthalate (Dacron) and hemostatic stitches with polytetrafluoroethylene (Teflon), passing below the vessel to contain blood leakage from the tear. In addition, the fibrin sealant patch (TachoSil, Baxter, Deerfield, IL, USA) with the adjunct of human fibrin glue (Tissucol, Baxter) can be used to achieve hemostasis [12].

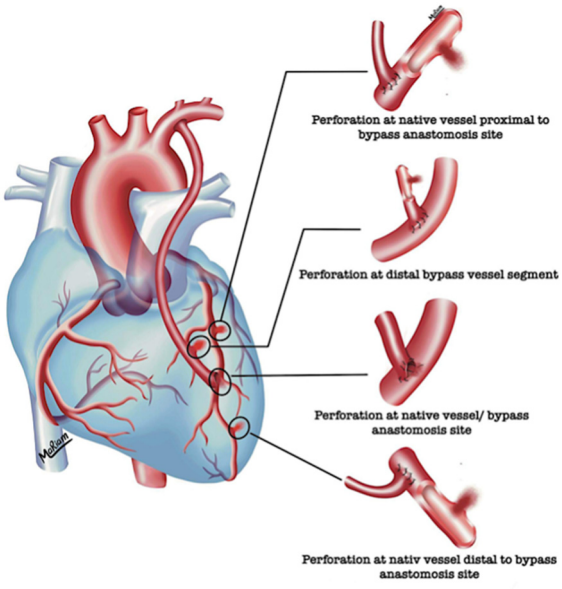
Thus, early recognition and immediate sealing before the initiation of the self-propagating process, regardless of the stable image of staining, as well as close monitoring, is imperative. In addition, diffuse bleeding could persist after successful but delayed percutaneous sealing. Moreover, a second control image could be necessary, regardless of the first stable image of staining, to demonstrate the dynamicity of the injury.

2.5.5. Category V: Perforation of the Coronary Vessel Bypass Graft

The fifth category is the perforation of the coronary vessel bypass graft (CABG) (Figure 9A,B). CABG is prone to accelerated atherosclerosis and graft stenosis or even total occlusion, particularly in a vein graft. Complications specific to graft-PCI include no-reflow, distal embolization, stent restenosis, thrombosis, and perforation [30].



(**A**)



(**B**)

Figure 9. (**A**): Proximal perforation site scenarios of coronary artery bypass graft (CABG). (**B**): Distal perforation site scenarios of coronary artery bypass graft (CABG).

This category of perforation is challenging, although it could be protective from pericardial tamponade if the perforation occurs in the extracardiac course of the graft.

Thus, it can lead to extracardiac mediastinal progressive bleeding, causing mediastinal bleeding, hemothorax, hemorrhage, cardiogenic shock, and death [30,31]. However, if the extravasation persists, loculated effusion can lead to compression of the adjacent cardiac and extracardiac neighboring structures [26,32].

The treatment strategy differs depending on the perforation site. If a bypass perforation occurs in its extracardiac course or even after the anastomosis in the native coronary vessel, the management will be like that for native coronary vessel perforation.

On the other hand, the treatment of anastomosis site perforation is challenging because of the dual source of blood supply. Therefore, closure of antegrade or retrograde feeding vessels, using coils or the semi-stent crush technique, and covered stent implantation from bypass to native artery or native to native artery (Figure 10A,B), in order to adequately block the source of bleeding from both ends of the anastomosis site, would be necessary.

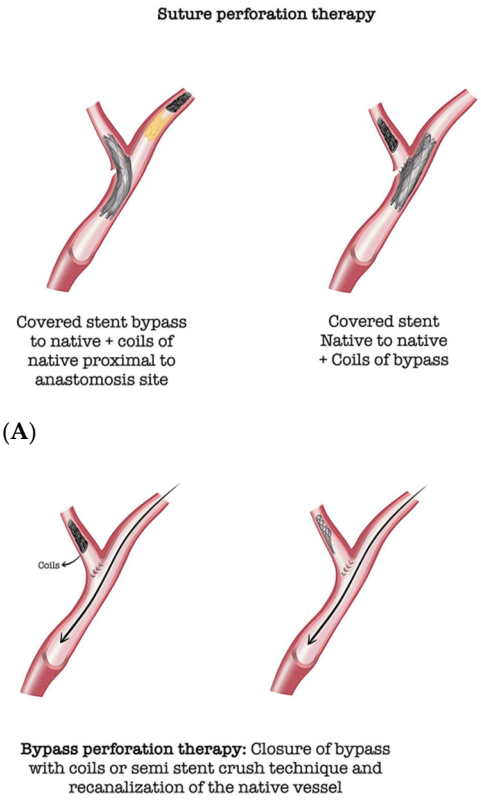


Figure 10. (**A**): Treatment of anastomosis site perforation is challenging because of the dual source of blood supply. Therefore, closure of antegrade or retrograde feeding vessels and covered stent implantation from bypass to native artery or native to native artery, in order to adequately block the source of bleeding from both ends of the anastomosis site, would be necessary. (**B**): Sealing of the bypass vessel proximal to the perforation site, using coils or the semi-stent crush technique, in order to adequately block the source of bleeding, would be necessary.

Finally, CT is still the gold standard and could play a crucial role in diagnosing the underlying pathology, understanding the mechanism of injury, demonstrating the adjacent structures being compressed, and guiding the management of both percutaneous (e.g., CT-guided drainage) and surgical intervention (Figure 11) [33]. Notably, transthoracic echocardiography can be misleading in such situations.

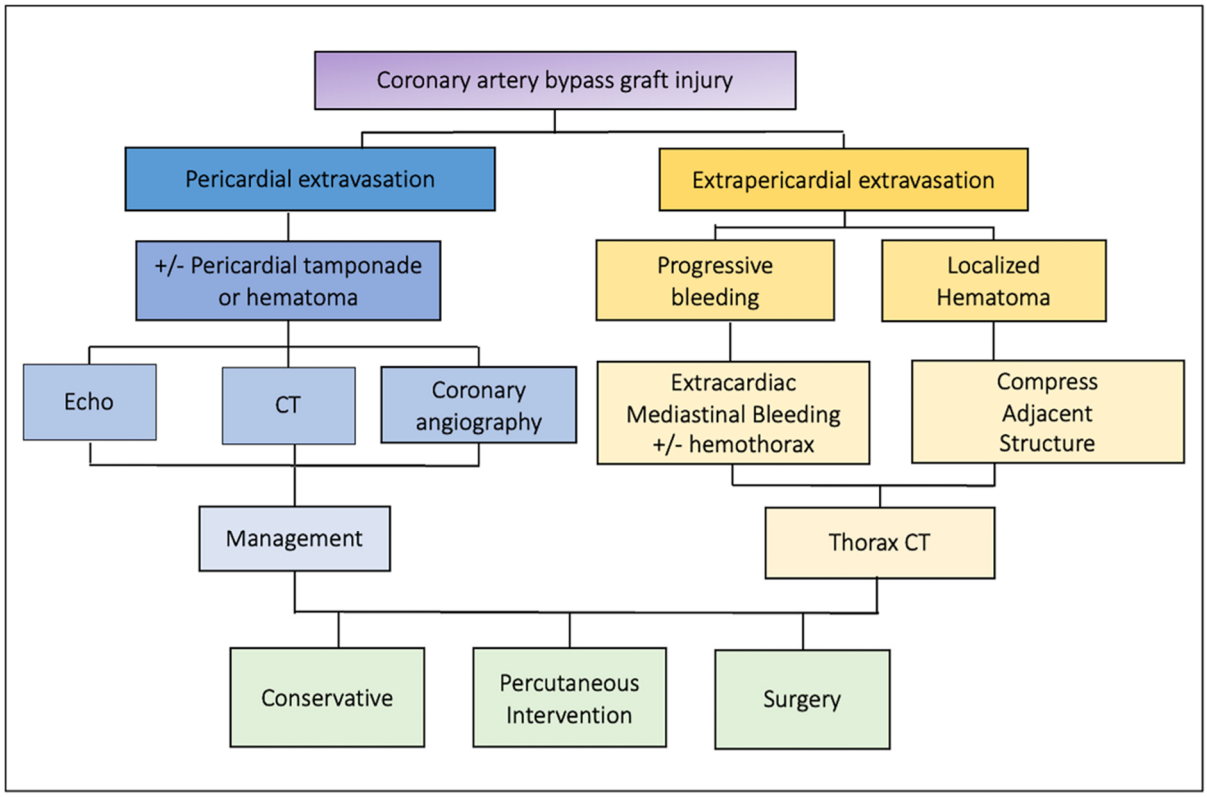


Figure 11. Management algorithm of coronary artery bypass graft perforation. Computer tomography plays a crucial role in diagnosing the underlying pathology, understanding the mechanism of injury, demonstrating the adjacent structures being compressed, and guiding the management of both percutaneous (e.g., CT-guided drainage) and surgical interventions.

3. Discussion

Coronary artery perforation after PCI—and how to treat this complication—is classified in the literature according to its severity using the Ellis classification [34]: type I, extra luminal carter without significant extravasation and without linear staining; type II, pericardial or myocardial extravasation with a hole of 1 mm; and type III, hole > 1 mm with frank extravasation or bleeding into another cardiovascular cavity. Type I CPs have an excellent overall prognosis. However, type II and III CPs have a higher rate of complications such as cardiac tamponade, hemodynamic collapse, and death, and poorer long-term outcomes, particularly for CAP III [34].

However, this classification and most other perforation algorithms simply focus on the proximal, distal, and collateral vessel injury and perforation into the anatomic cavity. They focus on the source of injury, not considering preventive and predictive measurement, the mechanism of injury, venous injury, the consequences of each injury, and how to deal with them efficiently.

In addition, the extravasation of blood either into the endocardium, causing the coronary steal phenomenon [27], or into the myocardium and pericardium, causing a hematoma that compresses neighboring structures during coronary intervention, is not fully discussed in the literature. This type of injury is very challenging as it gives the false impression that there is no source of bleeding or obvious pathology, although it exists [13,14,29,30,32].

The perforation algorithm in this article:

- Is straightforward, more comprehensive and starts with preventive measures;
- Highlights predicting the complication before it happens and preparing the operator to deal with it, as some complications are not preventable;

- Stresses early recognition of perforations to identify the source of bleeding and for understanding the mechanism of bleeding, as these steps will better influence the management strategy and outcome;
- Highlights the crucial role of imaging in prevention, prediction, device selection, understanding the site and mechanism of injury, and accompanying the management strategy;
- Summarizes how to stabilize the hemodynamic status by focusing on pericardiocentesis indication, the reversal of anticoagulation, and hemodynamic support as a case-by-case decision according to the situation, if necessary;
- Classifies the cause of bleeding into five categories, each of which has a different causal mechanism and subsequently differs in management;
- Highlights the challenges and difficulties in diagnosing and managing the cardiac wall hematoma, taking into consideration a hematoma that deteriorates the hemodynamic status without effusion "dry tamponade" and how it can mask the situation with false impressions that there is no source of bleeding or obvious pathology;
- Stresses the importance of early recognition and immediate sealing before the initiation of the self-propagating process (avulsed capillary vessels providing active bleeding that fuels its expansion), regardless of the stable image of staining, as well as the role of close monitoring and a second control image to demonstrate the dynamicity of the injury (diffuse bleeding could persist after successful but delayed percutaneous sealing);
- Highlights coronary steal phenomena and their consequences;
- Stresses CABG perforation as a separate category, as this type of perforation is challenging and differs in management depending on the site of injury (cardiac or extracardiac) [32].

Recently, the role of innovative percutaneous intervention has increased, offering the possibility first of catheter-based intervention to take place, and then the surgical option, if the percutaneous one fails.

The available techniques for the treatment of perforations often necessitate dedicated equipment and expertise.

For example, perforation of the great cardiac vein after Cx PCI can be managed with a catheter as follows: first, intubate the coronary sinus and try to wire the great cardiac vein; then, use a bailout prolonged balloon or covered stent implantation to stop the bleeding (Figure 2) [7].

In addition, imaging information about cardiac vessel injury is useful for a better understanding of the spatial orientation of the coronary vessels, in order to detect a hematoma that deteriorates the hemodynamic status without effusion "dry tamponade" and could have a particular role in cardiac interventions to predict and prevent this complication [33].

Moreover, early introduction of intracoronary imaging may guide a safe PCI strategy in terms of device selection [10]. For example, a unique IVUS image before intervention may predict coronary artery rupture if a C-type CAlcified and residual Thin plaque sign (C-CAT sign) exists [35]. Therefore, using a smaller balloon size or de-bulking devices such as orbital atherectomy and rotational atherectomy could prevent coronary artery rupture in such cases.

However, perforation could involve diagnostic and therapeutic challenges, extending into situations where the coronary injury could not be predictable or preventable even with meticulous attention and gentle equipment handling. Therefore, interventional cardiologists should take precautions to avoid CAP, try to recognize it early if it occurs, and become familiar with general and type-specific approaches to manage it adequately.

4. Conclusions

- Coronary perforation is a potentially life-threatening complication in all patients undergoing percutaneous coronary intervention. Thus, it is crucial for interventional cardiologists to take precautions to avoid this complication.
- In this context, the cardiac vessel perforation algorithm could be more comprehensive and cover the preventive measures and predictors, take into consideration prompt recognition, implement actions to restabilize the hemodynamic status, highlight understanding the source and mechanism of bleeding, and classify the cause of bleeding into type-specific approaches to manage it adequately, as each causality would necessitate a different management strategy for a successful outcome.
- Invasive coronary imaging may guide a safe PCI strategy in terms of the device.

What this article adds

The perforation algorithm in this article:

- Is more comprehensive and starts with preventive measures;
- Highlights predicting the complication before it happens and preparing the operator to deal with it, as some complications are not preventable;
- Stresses early recognition of perforations to identify the source of bleeding and understand the mechanism of bleeding, as these steps will better influence the management strategy and outcome;
- Summarizes how to stabilize the hemodynamic status by focusing on pericardiocentesis indication, the reversal of anticoagulation, and hemodynamic support according to the situation, if necessary;
- Classifies the cause of bleeding into five categories, each of which has a different causal mechanism and subsequently differs in management;
- Highlights the challenges and difficulties in diagnosing and managing the cardiac wall hematoma, taking into consideration a hematoma that deteriorates the hemodynamic status without effusion "dry tamponade" and how it can mask the situation with false impressions that there is no source of bleeding or obvious pathology;
- Stresses the importance of early recognition and immediate sealing before the self-propagating process initiation (avulsed capillary vessels providing active bleeding that fuels its expansion), regardless of the stable image of staining, as well as the role of close monitoring and a second control image to demonstrate the dynamicity of the injury (diffuse bleeding could persist after successful but delayed percutaneous sealing);
- Highlights coronary steal phenomena and their consequences;
- Uses a guide catheter extension to temporarily seal the proximal or medial vessel injury, allowing the intervention to proceed at the distal part of the vessel without interruption;

How this algorithm might affect practice:

- We reformatted a new coronary perforation algorithm. It starts with prevention and prediction, goes through understanding the source and mechanism of bleeding, and finally classifies the cause of bleeding into vessel, pericardial, myocardial, and chamber perforation, as each causality necessitates a different management strategy to improve outcomes.

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Abbreviations

CABG	Coronary artery bypass graft surgery
CAP	Coronary artery perforation
C-CAT	C-type Calcified and residual Thin plaque
CT	Computer tomography
CTO	Chronic total occlusion
CVS	Cardiac venous system
GCV	Great cardiac vein
PCI	Percutaneous coronary intervention
PTFE	Poly-tetrafluorethylene

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