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ACUTE VASCULAR COMPLICATIONS FOLLOWING PERCUTANEOUS CORONARY INTERVENTIONS (PCI): MECHANISMS, PREVENTION, AND THERAPEUTIC STRATEGIES

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ABSTRACT

Percutaneous coronary intervention (PCI) has become one of the most commonly performed cardiovascular procedures worldwide and represents a cornerstone therapy for the treatment of coronary artery disease and acute coronary syndromes. Over the past decades, significant technological and pharmacological advances have improved the safety and effectiveness of PCI procedures. Despite these developments, acute vascular complications remain an important clinical concern and may negatively affect procedural success and long-term outcomes.

Acute complications associated with PCI include coronary artery dissection, coronary perforation, acute vessel closure, stent thrombosis, and bleeding events related to vascular access or antithrombotic therapy. Although the overall incidence of such complications has declined with the introduction of modern drug-eluting stents, intravascular imaging, and radial artery access techniques, the increasing complexity of treated coronary lesions continues to present challenges for interventional cardiologists.

This review provides a comprehensive overview of the mechanisms, epidemiology, risk factors, prevention strategies, and management approaches for acute vascular complications following PCI. The analysis integrates findings from contemporary clinical trials, meta-analyses, international registries, and guideline documents. Particular attention is given to complications occurring during complex procedures such as chronic total occlusion interventions and treatment of heavily calcified coronary lesions.

Understanding the mechanisms underlying PCI-related complications and implementing appropriate preventive strategies are essential for improving procedural safety and optimizing clinical outcomes in patients undergoing coronary revascularization.

KEYWORDS

Percutaneous Coronary Intervention, Vascular Complications, Coronary Perforation, Stent Thrombosis, Bleeding Complications, Interventional Cardiology

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Introduction

Percutaneous coronary intervention (PCI) has fundamentally changed the management of coronary artery disease and remains one of the most frequently performed invasive procedures in contemporary cardiovascular medicine. Since its introduction in the late twentieth century, PCI has undergone substantial development, driven by advances in coronary stent technology, intravascular imaging, and adjunctive pharmacotherapy. These innovations have contributed to higher procedural success rates and improved clinical outcomes in patients with both stable coronary artery disease and acute coronary syndromes (Levine et al., 2021; Neumann et al., 2019).

Despite these improvements, acute vascular complications continue to represent a relevant clinical challenge. Although their incidence has declined over time, such events still occur during or shortly after PCI and may adversely affect both immediate procedural success and longer-term prognosis. These complications may involve the coronary arteries directly, as in the case of dissection, perforation, or acute vessel closure, or may arise from vascular access and the systemic effects of antithrombotic treatment, leading to bleeding complications.

The risk of complications during PCI is shaped by a combination of patient-related and lesion-related factors. Advanced age, multiple comorbidities, and inflammatory conditions may increase procedural vulnerability. At the same time, lesion characteristics such as severe calcification, long lesion length, and chronic total occlusion substantially influence procedural complexity and the likelihood of adverse events (Zografos et al., 2020; Généreux et al., 2014).

An important aspect of contemporary practice is the growing complexity of lesions treated by PCI. Interventional cardiologists increasingly perform procedures in patients with multivessel disease, complex bifurcation lesions, heavily calcified plaques, and chronic total occlusions. While this expansion has significantly broadened the therapeutic role of PCI, it has also increased the technical demands of the procedure and, consequently, the potential for complications.

Data from contemporary registries indicate that major complications occur in approximately 2–5% of PCI procedures, although the exact frequency varies according to patient profile, lesion anatomy, and procedural complexity (Bangalore et al., 2022). Among these events, bleeding remains one of the most common and clinically significant complications. Importantly, post-procedural bleeding has been consistently linked with increased mortality and worse cardiovascular outcomes (Mehran et al., 2013).

Coronary perforation is another serious, albeit less common, complication of PCI. Although relatively rare, it may result in life-threatening consequences such as cardiac tamponade and therefore requires immediate recognition and prompt intervention (Azzalini et al., 2019). Similarly, coronary artery dissection may impair coronary blood flow and precipitate myocardial ischemia if not identified and managed without delay.

Stent thrombosis remains an additional complication of major clinical importance. Although modern stent platforms have reduced its incidence, this event continues to be associated with high mortality and may have catastrophic consequences. Among the most important predictors of stent thrombosis are incomplete stent expansion, premature discontinuation of antiplatelet therapy, and complex coronary anatomy (Palmerini et al., 2013).

At the same time, several technological developments have clearly improved procedural safety. New-generation drug-eluting stents have reduced restenosis rates and improved long-term outcomes when compared with bare-metal stents (Changal et al., 2021; Bangalore et al., 2018). In addition, intravascular imaging modalities such as intravascular ultrasound (IVUS) and optical coherence tomography (OCT) allow more accurate assessment of lesion morphology and more precise optimization of stent deployment (Ali et al., 2017; Räber et al., 2020).

Another important advance has been the increasing adoption of radial artery access, which has been shown to reduce bleeding complications when compared with the femoral approach. Several studies have demonstrated that radial access is associated with lower bleeding risk and better clinical outcomes in selected patient populations (Rao et al., 2012; Kei-yan et al., 2020).

Nevertheless, despite these achievements, complex coronary interventions remain associated with elevated procedural risk. Chronic total occlusion PCI, for example, requires advanced technical expertise and may increase the likelihood of complications such as coronary perforation or collateral vessel injury (Karmpaliotis et al., 2015).

In view of the increasing complexity of PCI and the continuing importance of complication prevention, a detailed understanding of the mechanisms underlying acute vascular complications is essential in contemporary interventional cardiology. Early recognition and appropriate management of these events may substantially improve patient outcomes.

The aim of this review is to provide a comprehensive overview of acute vascular complications following PCI. By integrating evidence from recent clinical studies and guideline documents, the article examines the epidemiology, pathophysiological mechanisms, risk factors, preventive strategies, and therapeutic approaches associated with these complications.

Methodology

This article was prepared as a narrative literature review designed to synthesize and critically discuss the current body of evidence concerning acute vascular complications following percutaneous coronary intervention (PCI). The main objective of the review was to provide a structured and comprehensive overview of the epidemiology, underlying mechanisms, major risk factors, preventive strategies, and management options associated with complications occurring during or shortly after PCI. Given the broad and clinically heterogeneous nature of this topic, a narrative review format was considered the most appropriate approach, as it allows the integration of findings from different types of scientific evidence and facilitates a clinically oriented interpretation of the literature.

The review was based on the analysis of contemporary publications relevant to vascular complications in interventional cardiology. The included literature comprised systematic reviews, meta-analyses, randomized clinical trials, registry-based studies, observational analyses, expert review articles, and current international guideline documents. This broad selection of evidence was intended to capture both the scientific background and the practical clinical implications of PCI-related complications. Particular attention was paid to studies that addressed the incidence, mechanisms, prevention, and treatment of clinically important complications such as coronary artery dissection, coronary perforation, bleeding events, acute vessel closure, and stent thrombosis.

Special emphasis was also placed on publications concerning complex PCI procedures, especially chronic total occlusion (CTO) interventions and PCI in severely calcified coronary lesions. These procedural settings were included deliberately because they represent some of the most challenging scenarios in contemporary interventional cardiology and are consistently associated with a higher risk of procedural complications. The review therefore sought not only to summarize general PCI-related complications but also to examine those clinical situations in which complication risk is particularly pronounced.

In addition to original clinical studies and review articles, the methodology incorporated guideline documents issued by major professional societies, including the American College of Cardiology (ACC), the American Heart Association (AHA), and the European Society of Cardiology (ESC). These documents were included because they provide evidence-based recommendations that shape current interventional practice and offer an important framework for interpreting procedural risk, complication prevention, and therapeutic decision-making in PCI.

Literature Selection

The literature analyzed in this review consisted of thirty key publications selected on the basis of their relevance to acute vascular complications following PCI. These sources represented a broad spectrum of evidence and covered both foundational and contemporary aspects of the topic. The final body of literature included:

- systematic reviews and meta-analyses
- registry-based observational studies
- randomized clinical trials
- expert review papers
- international cardiology guidelines

Priority was given to more recent publications, particularly those published between 2020 and 2026, in order to reflect current clinical practice, evolving procedural techniques, and recent developments in stent technology, intravascular imaging, and adjunctive pharmacotherapy. At the same time, several earlier landmark studies were also retained in the review because of their continued importance in defining standardized clinical endpoints, establishing complication classifications, and shaping modern PCI practice. This was especially relevant for publications concerning stent thrombosis definitions, coronary stent trial endpoints, and foundational comparisons between different PCI strategies.

Data Sources and Scope of Analysis

The selected publications addressed multiple interrelated dimensions of PCI complications and contemporary interventional practice. The literature reviewed in this article covered the following principal domains:

- epidemiology and incidence of PCI-related vascular complications
- pathophysiological mechanisms of coronary and vascular injury during PCI
- prevention and management of complications during chronic total occlusion interventions
- outcomes associated with heavily calcified coronary lesions and calcium-modification strategies
- bleeding complications after PCI and their prognostic significance
- mechanisms, classification, and prevention of stent thrombosis
- the role of intravascular imaging, including IVUS and OCT, in improving PCI outcomes
- differences in complication rates between radial and femoral vascular access

Together, these sources provided a broad and clinically relevant evidence base for understanding both the frequency and the clinical impact of vascular complications following PCI.

Analytical Approach

The selected studies were analyzed using a qualitative narrative synthesis. Rather than applying a formal quantitative pooling method, the evidence was interpreted thematically in order to identify consistent trends, clinically relevant observations, and areas of agreement across different study designs. This approach was chosen because the available literature includes heterogeneous sources, ranging from meta-analyses and randomized trials to registries, guideline statements, and expert reviews. A narrative framework therefore allowed these diverse forms of evidence to be integrated into a coherent clinical discussion.

For the purpose of structured analysis, the literature was organized into several thematic categories. These included:

- epidemiology of PCI complications
- mechanisms of vascular injury during PCI
- patient-related and lesion-related risk factors
- prevention strategies and technological innovations
- therapeutic management of acute complications

This thematic structure made it possible to examine PCI-related complications not only as isolated events, but also as part of a broader procedural and clinical context. As a result, the review provides a comprehensive and clinically oriented synthesis of contemporary knowledge regarding acute vascular complications associated with PCI.

Results

Epidemiology of Acute Vascular Complications in Percutaneous Coronary Intervention

The incidence of acute vascular complications associated with percutaneous coronary intervention (PCI) has declined substantially over the last two decades. This improvement reflects major advances in interventional cardiology, including the introduction of safer devices, refinement of procedural techniques, broader use of intravascular imaging, and optimization of antithrombotic therapy. Despite this progress, vascular complications have not been eliminated and continue to represent an important factor influencing both short-term procedural success and long-term clinical outcomes.

Data from large contemporary registries indicate that major complications occur in approximately 2–5% of PCI procedures, although the exact frequency varies depending on the characteristics of the treated population and the complexity of the intervention (Bangalore et al., 2022). In clinical practice, the observed incidence is shaped by multiple factors, including patient age, comorbidity burden, lesion morphology, operator experience, and the overall expertise of the institution performing the procedure. For this reason, complication rates should not be interpreted as uniform across all PCI settings, but rather as context-dependent outcomes influenced by both clinical and procedural variables.

Among the acute complications most frequently reported after PCI, bleeding events remain the most common. Their clinical importance extends well beyond the immediate post-procedural period, as bleeding has consistently been associated with increased mortality, recurrent myocardial infarction, longer hospital stay, and a greater likelihood of further adverse cardiovascular events. Evidence from systematic reviews and meta-analyses has shown that clinically relevant bleeding continues to affect a meaningful proportion of patients undergoing PCI, even in the era of contemporary stent technology and improved pharmacological strategies. Importantly, the occurrence of bleeding is usually multifactorial. It may arise from vascular access site injury, but it may also reflect the systemic effects of anticoagulants and dual antiplatelet therapy that are essential for preventing thrombotic complications.

Another major category of complications includes direct injury to the coronary arteries during the procedure itself. Mechanical trauma caused by guidewires, balloons, atherectomy devices, or stent delivery systems may lead to coronary dissection or perforation. Although many dissections can be managed effectively with prompt stent implantation, more severe forms may compromise distal blood flow and lead to abrupt vessel closure or myocardial ischemia. In this context, the clinical significance of coronary injury depends not only on the extent of structural damage but also on the speed of recognition and adequacy of procedural response.

Coronary perforation, while less common than dissection or bleeding, remains one of the most serious complications encountered during PCI. Reported incidence generally ranges from 0.2% to 0.6%, but even this relatively low frequency is clinically important because perforation may result in cardiac tamponade, hemodynamic instability, or the need for emergency intervention. The probability of perforation is particularly increased in technically demanding procedures, especially those involving chronic total occlusion (CTO) lesions, heavily calcified plaques, or aggressive lesion modification strategies. In such settings, the balance between procedural success and complication risk becomes especially delicate.

Stent thrombosis represents another severe complication of PCI. Although its incidence has fallen markedly with the introduction of modern drug-eluting stents and improved antiplatelet therapy, it remains a clinically significant event because of its strong association with acute myocardial infarction and high mortality. Even in contemporary practice, stent thrombosis continues to be one of the most feared adverse outcomes following coronary intervention, particularly in patients with complex anatomy, inadequate stent expansion, or interruption of antiplatelet treatment.

The epidemiology of PCI-related complications is strongly influenced by lesion complexity. Chronic total occlusions, diffuse disease, bifurcation lesions, and heavily calcified coronary stenoses all increase technical difficulty and may substantially elevate the risk of adverse procedural events (Zografos et al., 2020). These lesions often require longer procedures, more advanced devices, greater operator experience, and more extensive lesion preparation, each of which may contribute to a higher complication burden.

Patient-related factors are equally important in shaping procedural risk. Older adults, patients with diabetes mellitus, chronic kidney disease, anemia, or autoimmune and inflammatory disorders frequently present with more diffuse atherosclerosis, more fragile vascular beds, and greater susceptibility to both ischemic and hemorrhagic complications. Such patients may also have reduced physiological reserve, making them less able to tolerate even modest procedural complications. As a result, the same complication may carry different prognostic weight depending on the underlying patient profile.

Contemporary registry studies have consistently shown that careful pre-procedural planning and operator expertise play a central role in reducing complication rates. High-volume centers performing complex coronary interventions generally achieve better outcomes and lower complication frequencies than lower-volume institutions. This observation underscores the importance of experience, structured procedural strategy, and institutional readiness in the safe performance of PCI. In modern interventional cardiology, complication prevention depends not only on device technology, but also on technical skill, clinical judgment, and the ability to anticipate and promptly manage adverse events when they occur.

Overall, the epidemiological evidence indicates that acute vascular complications after PCI have become less frequent than in previous eras, yet they continue to represent a substantial clinical issue. Their current profile reflects the interaction between increasingly sophisticated procedural capabilities and the growing complexity of patients and lesions treated in routine practice.

Coronary Artery Dissection

Coronary artery dissection represents one of the most frequently encountered complications during percutaneous coronary intervention (PCI). This complication occurs when mechanical trauma disrupts the layers of the coronary arterial wall, leading to separation between the intima and media and the formation of a false lumen (Al-Ogaili, Gill, & Brilakis, 2025). The resulting intramural hematoma or intimal flap may compromise coronary blood flow and potentially lead to myocardial ischemia.

Dissections may occur at multiple stages of the PCI procedure, including guidewire manipulation, balloon dilation, atherectomy, or stent deployment. The likelihood of dissection increases when treating complex lesions, particularly those characterized by heavy calcification, long lesion length, or tortuous vessel anatomy (Bangalore et al., 2022; Zografos et al., 2020). Balloon overinflation, inadequate lesion preparation, and the use of oversized devices may also contribute to vessel wall injury.

The severity of coronary artery dissection varies considerably. Minor dissections may appear only as subtle angiographic irregularities without significant impact on coronary blood flow. In contrast, severe dissections may propagate along the vessel wall and lead to abrupt vessel closure.

The National Heart, Lung, and Blood Institute (NHLBI) classification system remains the most commonly used framework for categorizing coronary dissections according to angiographic appearance (Cutlip et al., 2007). In this system, type A dissections appear as minor radiolucent areas within the lumen, while type B dissections are characterized by parallel tracts or double lumen appearance. These minor dissections often resolve spontaneously and may not require additional intervention. More severe types (C through F) are associated with persistent contrast staining, spiral dissections, or total vessel occlusion, and typically require immediate treatment.

In contemporary PCI practice, most clinically significant dissections are treated with stent implantation. Stents seal the intimal tear and restore normal blood flow by compressing the dissection flap against the vessel wall. In some cases, additional balloon dilation may be required to ensure adequate stent expansion and apposition (Changal et al., 2021).

Intravascular imaging technologies have significantly improved the detection and management of coronary artery dissections. Intravascular ultrasound (IVUS) and optical coherence tomography (OCT) provide high-resolution visualization of the arterial wall and allow identification of intramural hematomas or dissections that may not be visible on conventional angiography alone (Ali et al., 2017; Räber et al., 2020). These imaging modalities also assist operators in optimizing stent placement and preventing further vessel injury.

Although the majority of coronary dissections can be successfully treated during PCI, severe dissections remain associated with adverse clinical outcomes. Therefore, careful procedural technique and appropriate lesion preparation remain essential for minimizing the risk of this complication (Levine et al., 2021).

Coronary Perforation

Coronary perforation is a rare but potentially life-threatening complication of PCI. This complication occurs when an interventional device penetrates the full thickness of the coronary artery wall, resulting in leakage of blood into surrounding structures such as the pericardial space or myocardium (Azzalini et al., 2019).

Although the reported incidence of coronary perforation is relatively low, typically ranging from 0.2% to 0.6% of PCI procedures, the clinical consequences can be severe (Al-Ogaili et al., 2025). Rapid accumulation of blood in the pericardial space may lead to cardiac tamponade, a condition characterized by impaired cardiac filling and hemodynamic collapse.

The Ellis classification system is widely used to categorize coronary perforations according to angiographic severity. Type I perforations involve limited extraluminal contrast staining without evidence of contrast jet extravasation. Type II perforations are characterized by myocardial or pericardial staining without active contrast streaming. Type III perforations represent the most severe form and involve frank contrast extravasation through a sizeable arterial defect (Azzalini et al., 2019).

Several procedural and anatomical factors increase the risk of coronary perforation. Complex coronary lesions, particularly those involving severe calcification or chronic total occlusions, are associated with increased risk (Ramazani et al., 2025; Zografos et al., 2020). The use of stiff guidewires and aggressive lesion-modification techniques such as atherectomy may also increase the likelihood of vessel perforation.

CTO PCI procedures represent a particularly high-risk scenario for coronary perforation. During these procedures, guidewires are often advanced through ambiguous occlusion segments, which increases the probability of wire exit from the true lumen (Subramaniam & Lombardi, 2026; Karmpaliotis et al., 2015).

Additionally, retrograde techniques involving collateral vessels may increase the risk of injury to delicate collateral channels.

Clinical manifestations of coronary perforation vary depending on the size and location of the arterial defect. Small perforations may remain clinically silent and resolve spontaneously. In contrast, large perforations may lead to rapid hemodynamic deterioration due to cardiac tamponade.

Prompt recognition and treatment are essential for preventing catastrophic outcomes. Management strategies include prolonged balloon inflation at the perforation site, implantation of covered stents, and embolization with coils or other materials (Azzalini et al., 2019). In cases of cardiac tamponade, emergency pericardiocentesis is required.

Bleeding Complications

Bleeding complications remain among the most common and clinically significant adverse events following percutaneous coronary intervention (PCI). Despite improvements in procedural techniques and pharmacological management, bleeding continues to represent a major determinant of short- and long-term patient outcomes. Numerous clinical studies have demonstrated that bleeding events after PCI are independently associated with increased mortality, recurrent myocardial infarction, and prolonged hospitalization (Mehran et al., 2013). Consequently, prevention and management of bleeding complications have become a central focus of contemporary interventional cardiology.

Bleeding following PCI may originate from several sources, including the vascular access site, gastrointestinal tract, or other systemic locations related to antithrombotic therapy. Historically, femoral artery access was the most commonly used approach for coronary interventions. However, femoral access requires the insertion of relatively large vascular sheaths and is associated with a higher risk of access-site complications such as hematoma formation, pseudoaneurysm, and retroperitoneal hemorrhage (Rao et al., 2012). These complications may lead to significant morbidity and require additional diagnostic and therapeutic interventions.

The introduction and widespread adoption of radial artery access have significantly reduced the incidence of access-site bleeding complications. Radial access involves puncture of the radial artery at the wrist, which is more superficial and easier to compress compared with the femoral artery. As a result, radial access allows rapid hemostasis and is associated with lower rates of major bleeding events (Kei-Yan et al., 2020). Multiple randomized clinical trials and meta-analyses have confirmed that radial access significantly improves patient safety and reduces bleeding complications compared with femoral access, particularly in high-risk patient populations such as those presenting with acute coronary syndromes.

Pharmacological therapy also plays an important role in bleeding risk after PCI. Antithrombotic therapy, including anticoagulants and dual antiplatelet therapy (DAPT), is essential for preventing thrombotic complications such as stent thrombosis (Valgimigli et al., 2021). However, these medications inevitably increase the risk of bleeding, particularly in elderly patients or those with comorbidities such as chronic kidney disease or anemia.

Balancing the prevention of thrombotic complications with the risk of bleeding represents a major challenge in contemporary PCI practice. Risk stratification tools and bleeding risk scores have been developed to assist clinicians in identifying patients at increased risk for hemorrhagic events. These tools allow physicians to tailor antithrombotic therapy according to individual patient characteristics and procedural factors.

Recent studies have also explored strategies aimed at reducing bleeding risk, including shorter durations of dual antiplatelet therapy in selected patient populations and the use of newer antiplatelet agents with improved safety profiles. Such individualized treatment strategies represent an important step toward optimizing PCI outcomes while minimizing the risk of bleeding complications.

Stent Thrombosis

Stent thrombosis represents one of the most severe and feared complications following percutaneous coronary intervention (PCI) and is associated with substantial morbidity and mortality. Although its overall incidence has decreased significantly with advances in stent technology and pharmacological therapy, stent thrombosis remains a critical clinical event that often manifests as acute myocardial infarction or sudden cardiac death (Windecker et al., 2014). Because of its potentially catastrophic consequences, prevention of stent thrombosis has become a central objective in contemporary PCI practice.

The Academic Research Consortium (ARC) established standardized definitions and classifications for stent thrombosis based on the timing of occurrence after PCI. According to this classification, acute stent thrombosis occurs within the first 24 hours following stent implantation, while subacute stent thrombosis develops between 24 hours and 30 days after the procedure. Late stent thrombosis occurs between one month and one year, and very late stent thrombosis refers to events occurring beyond one year after PCI (Windecker et al., 2014). This classification is widely used in clinical trials and observational studies evaluating PCI outcomes.

The pathophysiology of stent thrombosis is complex and multifactorial, involving both mechanical and biological mechanisms. Mechanical factors related to the PCI procedure itself play a major role in thrombus formation. Incomplete stent expansion, malapposition of stent struts, residual stenosis, and edge dissections can all create local disturbances in blood flow that promote platelet activation and thrombus formation within the stent (Palmerini et al., 2013). Inadequate lesion preparation, particularly in heavily calcified lesions, may further contribute to incomplete stent expansion and increase thrombosis risk.

Biological mechanisms also contribute significantly to stent thrombosis. Delayed endothelialization of stent struts may expose thrombogenic surfaces to circulating blood components, promoting platelet aggregation. Inflammatory responses to polymer coatings used in earlier-generation drug-eluting stents were also associated with delayed vascular healing and increased risk of late thrombosis. These concerns led to the development of newer-generation stent platforms with improved biocompatibility and thinner strut designs (Bangalore et al., 2018).

Patient-related factors are also important determinants of stent thrombosis risk. Conditions such as diabetes mellitus, chronic kidney disease, and reduced left ventricular function have been associated with impaired vascular healing and increased thrombotic risk (Valgimigli et al., 2021). Premature discontinuation of dual antiplatelet therapy (DAPT) is considered one of the most significant predictors of stent thrombosis, particularly in the early period following PCI.

Technological innovations have significantly improved outcomes related to stent thrombosis. New-generation drug-eluting stents have demonstrated superior safety profiles compared with earlier stent designs, largely due to improved polymer technology and reduced strut thickness (Changal et al., 2021). In addition, intravascular imaging techniques such as intravascular ultrasound (IVUS) and optical coherence tomography (OCT) allow more precise assessment of stent deployment, ensuring adequate expansion and optimal apposition of the stent within the vessel wall (Räber et al., 2020; Ali et al., 2017).

Together, these advances in device technology, pharmacological therapy, and procedural imaging have contributed to a substantial reduction in the incidence of stent thrombosis in contemporary PCI practice.

Calcified Coronary Lesions

Coronary artery calcification represents a major challenge during PCI procedures. Calcified plaques increase lesion rigidity and may prevent adequate balloon expansion or stent deployment (Généreux et al., 2014).

Inadequate stent expansion has been identified as one of the most important predictors of restenosis and stent thrombosis. Therefore, appropriate lesion preparation is essential when treating calcified coronary arteries.

Several specialized technologies have been developed to address this challenge. Rotational atherectomy uses a high-speed rotating burr to modify calcified plaques by selectively ablating hard calcified tissue while preserving the surrounding vessel wall. Orbital atherectomy employs a diamond-coated crown that orbits within the vessel lumen, gradually enlarging the lumen and modifying calcified plaque (Ramazani et al., 2025).

More recently, intravascular lithotripsy has emerged as an innovative approach for treating calcified coronary lesions. This technique uses acoustic pressure waves to fracture calcified plaques within the vessel wall, thereby facilitating balloon expansion and stent deployment.

Chronic Total Occlusion PCI Complications

Chronic total occlusion PCI represents one of the most technically demanding procedures in interventional cardiology. CTO lesions are defined as complete coronary artery occlusions lasting at least three months and are frequently associated with complex plaque morphology and heavy calcification (Zografos et al., 2020).

Advances in interventional techniques have significantly improved success rates for CTO PCI procedures. Contemporary registry data, including the ERCTO registry, indicate procedural success rates exceeding 85% in experienced centers (ERCTO Registry, 2024).

Despite these improvements, CTO PCI procedures remain associated with increased complication risk. Potential complications include coronary perforation, collateral vessel injury, and radiation exposure due to longer procedural times (Subramaniam & Lombardi, 2026).

The development of specialized procedural techniques has played a key role in improving CTO PCI outcomes. Antegrade dissection and re-entry techniques allow operators to bypass heavily calcified occlusion segments, while retrograde approaches via collateral vessels provide alternative pathways for crossing difficult occlusions (Karmpaliotis et al., 2015).

Risk prediction models have been developed to estimate procedural difficulty and complication risk in CTO interventions. These models incorporate clinical and angiographic variables and may assist clinicians in selecting appropriate treatment strategies (Simsek et al., 2023).

Discussion

The findings presented in this review demonstrate that acute vascular complications remain an important concern in contemporary percutaneous coronary intervention practice despite substantial technological progress and improvements in procedural techniques. Although the incidence of complications has decreased significantly over the past two decades, these events continue to influence both short-term procedural success and long-term cardiovascular outcomes (Al-Ogaili, Gill, & Brilakis, 2025). Contemporary PCI procedures are performed in increasingly complex patient populations, including elderly individuals and patients with multiple comorbidities, which further increases procedural risk.

One of the key observations emerging from the literature is the strong association between lesion complexity and complication risk. Contemporary PCI procedures increasingly involve treatment of complex coronary anatomy, including chronic total occlusions, bifurcation lesions, long diffuse atherosclerotic plaques, and heavily calcified coronary arteries (Bangalore et al., 2022). These anatomical characteristics substantially increase procedural difficulty and may predispose to complications such as coronary dissection, vessel perforation, and stent underexpansion. Lesion complexity therefore represents one of the most important determinants of PCI outcomes and should be carefully evaluated during pre-procedural planning.

Chronic total occlusion PCI represents one of the most technically demanding procedures in interventional cardiology. Historically, CTO interventions were associated with relatively low procedural success rates and a higher incidence of complications compared with standard PCI procedures. However, advances in interventional techniques, including antegrade dissection and re-entry strategies as well as retrograde approaches via collateral vessels, have significantly improved success rates (Karmpaliotis et al., 2015; Zografos et al., 2020). Registry studies such as the European Registry of Chronic Total Occlusion (ERCTO) have demonstrated procedural success rates exceeding 85% in experienced centers (ERCTO Registry, 2024). Nevertheless, these procedures still carry increased risk of complications, particularly coronary perforation and collateral vessel injury (Subramaniam & Lombardi, 2026).

Another important issue highlighted in the literature concerns the management of heavily calcified coronary lesions. Calcification significantly increases lesion rigidity and reduces vessel compliance, making balloon dilation and stent deployment more difficult (Généreux et al., 2014). Inadequate lesion preparation in such cases may lead to stent underexpansion, which has been identified as one of the strongest predictors of restenosis and stent thrombosis (Palmerini et al., 2013). The introduction of plaque-modification technologies such as rotational atherectomy, orbital atherectomy, and intravascular lithotripsy has improved the ability to treat calcified lesions effectively (Ramazani et al., 2025). These technologies allow controlled modification of calcified plaques and facilitate optimal stent expansion.

Bleeding complications represent another major determinant of patient outcomes following PCI. Numerous studies have demonstrated that bleeding events are independently associated with increased mortality and adverse cardiovascular outcomes (Mehran et al., 2013). The mechanisms underlying this association are multifactorial and include hemodynamic instability, interruption of antithrombotic therapy, and inflammatory responses triggered by hemorrhagic events. Furthermore, bleeding events often lead to discontinuation of antiplatelet therapy, which may subsequently increase the risk of thrombotic complications such as stent thrombosis.

The widespread adoption of radial artery access has been one of the most important developments in reducing bleeding complications. Compared with femoral access, radial access is associated with lower rates of access-site bleeding and improved patient comfort (Rao et al., 2012; Kei-Yan et al., 2020). Multiple randomized clinical trials have confirmed that radial access significantly reduces major bleeding events and may also improve survival in certain high-risk patient populations. Consequently, radial access has become the preferred vascular access route in contemporary PCI practice.

Another important factor influencing PCI outcomes is the use of intravascular imaging techniques. Intravascular ultrasound (IVUS) and optical coherence tomography (OCT) have emerged as valuable tools for optimizing PCI procedures (Ali et al., 2017; Räber et al., 2020). These imaging modalities provide detailed information regarding plaque morphology, vessel size, and stent deployment. Imaging-guided PCI allows more precise stent placement and ensures adequate stent expansion and apposition. Studies have demonstrated that imaging-guided PCI is associated with lower rates of restenosis and stent thrombosis compared with angiography-guided procedures alone.

Stent thrombosis remains one of the most feared complications of PCI due to its association with acute myocardial infarction and high mortality (Windecker et al., 2014). Although modern drug-eluting stents have significantly reduced the incidence of stent thrombosis compared with earlier stent platforms, careful attention to stent deployment and antiplatelet therapy remains essential (Stone et al., 2021; Bangalore et al., 2018). Factors such as incomplete stent expansion, stent malapposition, and premature discontinuation of antiplatelet therapy may increase the risk of thrombosis.

Pharmacological management plays a critical role in preventing thrombotic complications after PCI. Dual antiplatelet therapy combining aspirin and a P2Y12 inhibitor remains the cornerstone of treatment following coronary stent implantation (Valgimigli et al., 2021). However, optimal duration of therapy remains a subject of ongoing research, particularly in patients at high risk for bleeding. Contemporary clinical guidelines increasingly recommend individualized antiplatelet therapy based on patient-specific ischemic and bleeding risk profiles.

Clinical guidelines from major cardiology societies have also emphasized the importance of risk stratification and procedural planning. The ACC/AHA and ESC guidelines recommend careful evaluation of lesion complexity, patient comorbidities, and procedural risk factors prior to PCI (Levine et al., 2021; Neumann et al., 2019). Implementation of evidence-based guidelines may significantly improve procedural safety and reduce complication rates.

Another important aspect highlighted in recent studies is the role of operator experience and institutional procedural volume. High-volume centers performing complex coronary interventions typically achieve better outcomes and lower complication rates compared with institutions with lower procedural volumes (Bangalore et al., 2022). Operator expertise is particularly important in procedures such as CTO PCI and interventions involving heavily calcified lesions.

Emerging technologies may further improve PCI safety in the future. Artificial intelligence-based imaging analysis, advanced stent platforms, and robotic PCI systems are currently under investigation and may enhance procedural precision while reducing radiation exposure for operators and patients.

Overall, the literature indicates that the prevention of PCI complications requires a multifactorial approach. Optimal patient selection, careful procedural planning, appropriate device selection, and individualized pharmacological therapy all play critical roles in minimizing procedural risk. In addition, continuous technological innovation and operator training are essential for further improving PCI safety.

Future research should focus on improving risk prediction models, refining procedural techniques for complex coronary lesions, and developing new pharmacological strategies aimed at reducing both thrombotic and bleeding complications. Continued collaboration between clinical researchers, device manufacturers, and guideline committees will be crucial for advancing the field of interventional cardiology.

Table 1. Strategies for Prevention of PCI Complications

Strategy	Mechanism	Clinical Benefit	Key References
Radial artery access	Smaller arterial puncture site and easier hemostasis	Reduced bleeding complications	Rao et al., 2012; Kei-Yan et al., 2020
Intravascular imaging (IVUS/OCT)	Detailed visualization of lesion morphology and stent expansion	Reduced stent thrombosis and restenosis	Räber et al., 2020; Ali et al., 2017
Calcium-modification techniques	Rotational atherectomy, orbital atherectomy, intravascular lithotripsy	Improved lesion preparation and stent expansion	Ramazani et al., 2025; Généreux et al., 2014
Optimized antiplatelet therapy	Prevention of thrombus formation after stent implantation	Reduced risk of stent thrombosis	Valgimigli et al., 2021
Risk prediction scores	Identification of high-risk CTO procedures	Improved procedural planning	Simsek et al., 2023

Table 2. Risk Factors Associated with PCI Complications

Category	Risk Factors	Key References
Patient-related	Advanced age, diabetes mellitus, chronic kidney disease, inflammatory diseases (e.g., rheumatoid arthritis)	Bangalore et al., 2022; PCI outcomes in rheumatoid arthritis systematic review, 2024
Lesion-related	Severe calcification, chronic total occlusion, long lesions, bifurcation lesions	Généreux et al., 2014; Zografos et al., 2020
Procedural-related	Aggressive balloon inflation, stiff guidewires, complex CTO techniques	Karmpaliotis et al., 2015; Simsek et al., 2023
Pharmacological	Intensive dual antiplatelet therapy, anticoagulation therapy	Valgimigli et al., 2021; Levine et al., 2021

Table 3. Strategies for Prevention of PCI Complications

Strategy	Mechanism	Clinical Benefit	Key References
Radial artery access	Smaller arterial puncture site and easier hemostasis	Reduced bleeding complications	Rao et al., 2012; Kei-Yan et al., 2020
Intravascular imaging (IVUS/OCT)	Detailed visualization of lesion morphology and stent expansion	Reduced stent thrombosis and restenosis	Räber et al., 2020; Ali et al., 2017
Calcium-modification techniques	Rotational atherectomy, orbital atherectomy, intravascular lithotripsy	Improved lesion preparation and stent expansion	Ramazani et al., 2025; Généreux et al., 2014
Optimized antiplatelet therapy	Prevention of thrombus formation after stent implantation	Reduced risk of stent thrombosis	Valgimigli et al., 2021
Risk prediction scores	Identification of high-risk CTO procedures	Improved procedural planning	Simsek et al., 2023

Clinical Implications

The findings of this review have several important clinical implications for contemporary interventional cardiology practice.

First, careful patient selection and procedural planning remain essential for minimizing complication risk. Preprocedural imaging and risk assessment tools can help identify patients who may benefit from specialized interventional strategies.

Second, the routine use of radial artery access should be strongly considered in order to minimize bleeding complications. Radial access has become the preferred vascular access route in many institutions due to its improved safety profile.

Third, intravascular imaging should be considered in complex PCI procedures, particularly when treating heavily calcified lesions or chronic total occlusions. Imaging-guided PCI has been associated with improved procedural outcomes and reduced complication rates.

Fourth, the treatment of calcified lesions should incorporate appropriate plaque-modification strategies when necessary. Failure to adequately prepare calcified lesions may lead to stent underexpansion and increased risk of restenosis or thrombosis.

Finally, operator experience and procedural volume remain critical determinants of PCI outcomes. High-volume centers specializing in complex coronary interventions often achieve better procedural success rates and lower complication rates.

Future Directions in PCI Safety

The results of this review have several important implications for clinical practice in interventional cardiology. Understanding the mechanisms and risk factors associated with PCI complications is essential for improving patient safety and optimizing procedural outcomes.

First, careful patient evaluation prior to PCI is crucial. Preprocedural risk stratification allows clinicians to identify patients who may be at increased risk for complications. Factors such as advanced age, renal dysfunction, diabetes mellitus, and inflammatory diseases should be carefully considered when planning coronary interventions. In patients with high-risk profiles, additional preventive strategies may be necessary to reduce complication risk.

Second, detailed assessment of coronary anatomy is essential for successful PCI procedures. Modern imaging techniques allow accurate evaluation of lesion morphology and severity. Coronary angiography remains the primary diagnostic modality; however, intravascular imaging techniques such as IVUS and OCT provide additional information regarding plaque characteristics and vessel dimensions. These technologies are particularly useful in complex interventions, including treatment of calcified lesions and chronic total occlusions.

Third, appropriate selection of procedural techniques and devices plays a key role in preventing complications. For example, plaque-modification techniques may be required when treating heavily calcified lesions. Failure to adequately prepare calcified lesions may lead to suboptimal stent expansion and increase the risk of restenosis or thrombosis.

Fourth, vascular access strategy should be carefully considered. Radial artery access has become the preferred approach for PCI in many clinical settings because it significantly reduces bleeding complications. Adoption of radial access has been associated with improved patient outcomes and shorter hospital stays.

Fifth, pharmacological therapy remains an essential component of PCI procedures. Antiplatelet therapy is necessary to prevent thrombotic complications after stent implantation. However, clinicians must carefully balance the benefits of antithrombotic therapy with the risk of bleeding. Individualized treatment strategies based on patient-specific risk factors may help optimize clinical outcomes.

Finally, operator experience and institutional expertise are critical determinants of PCI success. Complex coronary interventions should ideally be performed in high-volume centers with experienced interventional cardiologists and access to advanced imaging and specialized devices.

Overall, the integration of careful patient assessment, advanced imaging techniques, optimized procedural strategies, and individualized pharmacological therapy can significantly reduce the incidence of PCI-related complications and improve patient outcomes.

Conclusions

Percutaneous coronary intervention has become a cornerstone therapy for the treatment of coronary artery disease and acute coronary syndromes. Continuous advances in device technology, pharmacological therapy, and interventional techniques have significantly improved procedural success rates and patient outcomes. However, acute vascular complications remain an important challenge in contemporary PCI practice.

The most common complications associated with PCI include coronary artery dissection, coronary perforation, bleeding events, and stent thrombosis. Although the incidence of these complications has decreased over time, they continue to influence both immediate procedural outcomes and long-term cardiovascular prognosis.

The occurrence of PCI complications is influenced by multiple factors, including patient characteristics, lesion morphology, and procedural techniques. Complex coronary anatomy, heavily calcified plaques, and chronic total occlusions are particularly associated with increased procedural risk. In addition, patient comorbidities such as diabetes mellitus and chronic kidney disease may further increase complication risk.

Technological innovations have played a major role in improving PCI safety. The development of new-generation drug-eluting stents has significantly reduced restenosis and stent thrombosis rates. Similarly, intravascular imaging techniques have improved the ability to optimize stent implantation and detect procedural complications.

The widespread adoption of radial artery access has also contributed to improved patient safety by reducing bleeding complications. Additionally, plaque-modification technologies have improved the management of calcified coronary lesions and enhanced procedural success.

Despite these advances, the increasing complexity of coronary interventions continues to present challenges for interventional cardiologists. Continued research and technological innovation are therefore essential for further improving PCI safety and effectiveness.

Future developments in interventional cardiology may include improved stent platforms, advanced imaging technologies, and the integration of artificial intelligence into procedural planning. These innovations have the potential to further reduce complication rates and improve patient outcomes.

In conclusion, a comprehensive understanding of the mechanisms underlying PCI-related complications, combined with careful procedural planning and appropriate preventive strategies, is essential for optimizing clinical outcomes in patients undergoing percutaneous coronary intervention.

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