Heart Surgery Forum 2025; 28(1): E107–E119 https://journal.hsforum.com/
doi: 10.59958/hsf.8165

Review

The New Era of Coronary Angioplasty: How Cutting-Edge Technologies are Redefining Complex Interventions

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Submitted: 31 October 2024 Revised: 1 December 2024 Accepted: 9 December 2024 Published: 21 January 2025

Abstract

Interventional cardiologists have recently become increasingly entrusted with the treatment of frail patients with complex coronary anatomy. Additionally, calcified lesions (CLs) have become more common due to the continued increase in the older population worldwide, increasing the need for simpler treatment options for such complex lesions. Hence, numerous debulking tools have recently been developed to overcome the difficulties associated with the angioplasty of CLs and to optimize stent positioning and delivery. In addition, bifurcation lesions (BLs) have always been more challenging than other lesions, requiring more specialized tools and complex strategies. Finally, intravascular imaging (IVI) is becoming increasingly important in assessing the complexity of lesions and optimizing procedural approaches. This article provides an overview of how complex procedures should be approached, from the choice of access and catheter to the use of specialized devices developed to assist cardiac catheterization laboratory operators in these complex scenarios.

Keywords

complex percutaneous coronary intervention; calcific lesions; bifurcation lesions; microcatheter; debulking techniques; rotablator; intravascular imaging

Introduction

The increasing prevalence of older people worldwide has significant implications for interventional cardiology, particularly for the treatment of coronary artery disease (CAD). As the elderly make up an increasing proportion of patients undergoing percutaneous coronary intervention (PCI), interventional cardiologists are increasingly tasked with treating frail patients with complex coronary anatomy [1]. This demographic shift has posed several procedural challenges. In response to this growing need, technological advances have led to the development of specialized devices designed to optimize outcomes in these difficult scenarios.

Calcified lesions (CL) are more common in the elderly population, probably due to the cumulative effects of longstanding cardiovascular risk factors such as hypertension, diabetes and hyperlipidemia [2].

These calcifications create a challenging environment for PCI as they increase lesion stiffness, reduce vascular compliance and make stent expansion and deployment difficult [3]. Calcium deposits not only present a significant mechanical obstacle to balloon angioplasty and stent deployment, but are also associated with a higher rate of procedural failure and adverse clinical outcomes. The complexity of calcified lesions requires the use of advanced techniques and specialized devices to improve procedural success and reduce complications.

In addition to CL, bifurcation lesions (BL)—especially in true bifurcations—the treatment is inherently complex and requires a precise approach, adequate protection of the side branch and careful stent placement to avoid malpositioning or distortion of the stent [4]. These procedures often involve the use of multi-stent techniques, which increase the risk of restenosis, thrombosis and procedural failure if not performed with specialized skills and tools.

Given the complexity of treating these lesions, it is now clear that optimizing PCI is critical to achieving favorable patient outcomes. In particular, intravascular imaging (IVI) has become essential for the management of complex PCI, as emphasized in the 2024 ESC guidelines on chronic coronary syndrome (CCS) [5]. IVI is therefore an indispensable cornerstone for complex interventions.

This article provides a comprehensive overview of the specialized devices that have been developed to assist interventional cardiologists, with a focus on their application in the treatment of complex PCI. In addition, we will explore the features, benefits and limitations of these devices.

Optimal Arterial Access Choose

Traditionally, complex procedures were mainly performed via the femoral approach, as this required larger French devices. However, the use of the femoral artery is associated with a higher rate of access site complications [6]. Treatment of complex lesions often requires a longer procedure time and appropriate anticoagulation, which further increases the risk of severe access site complications associated with the femoral approach. In recent years, technological advances have facilitated the safe use of radial access, even in complex cases, by offering tools compatible with larger French-sized instruments [7]. In particular, the development of introducers such as the Glidesheath Slender™ (Terumo Ineteventional sistems; Somerset, New Jersey 08873 800.283.7866) has expanded the use of radial access in complex procedures. The proprietary thin-wall technology reduces the outer diameter of the introducer sheath by 1 Fr with the same inner diameter. This makes the Slender 7 Fr suitable for radial access with 7 Fr devices required for complex PCI procedures such as rotablation, bifurcation, left main coronary artery and chronic total occlusions (CTO). This design minimizes trauma to the radial artery by maintaining an outer diameter equivalent to 6 Fr. This transition allows operators to take advantage of the benefits of radial access, including reduced bleeding complications and faster patient recovery, without jeopardizing the success of the procedure.

How to Increase Catheter Support in Complex PCI

Effective support of the guiding catheter is essential for successful PCI. Understanding the key factors that influence catheter stability is critical for safe and efficient interventions.

The supportive force of a guide catheter is primarily determined by two factors: the angle between the guiding segment and the opposite aortic wall (with optimal support achieved at a 90-degree angle) and the degree of contact of the secondary curve of the catheter with the aortic wall. These factors are influenced by both the catheter design and the access route chosen. Two types of support come into play with guide catheters:

Passive support: this form of support relies on the rigidity, size and shape of the catheter to allow firm contact between the secondary curve and the opposite aortocoronary sinus or aortic wall without significant manipulation. Common passive support catheters, such as EBU, XB and Amplatz, often have longer tips that must be carefully inserted to avoid coronary dissection.

Active support: In contrast, active support involves strategic manipulation of the catheter to create additional supportive force. This may include placing the catheter deep in the aortic root or deep intubation for more stability. An example of this is the use of the "power position" technique with catheters such as Judkins Left (JL) or Ikari Left.

The Role of the Choice of Access Route

The choice of access route has a significant influence on catheter support as it determines the primary anchoring site. For right-sided transradial procedures, the brachiocephalic artery serves as the primary anchoring point, while the aortic arch provides support for transfemoral procedures. For right coronary artery (RCA) interventions, the left radial approach can provide stable support, while the right radial approach is preferable for left coronary artery (LCA) interventions. In elderly patients (over 75 years of age), the choice of the left radial approach may help to avoid the tortuosity of the innominate artery, which is common in this patient group [8].

Practical Considerations

Several factors should be considered when selecting a guide catheter, including the size of the aortic root, the location of the coronary ostium, the positioning of the lesion, and the presence of tortuosity or calcification.

- Choice of catheter: Catheters such as EBU and XB are recommended for left coronary artery procedures, while Amplatz Left (AL) is ideal for right coronary artery cases. For difficult cases involving either artery, the Ikari Left may provide better support with the "Power Position" technique.
- Larger French sizes: Opting for larger French sizes can improve passive support during PCI.
- Longer sheaths for greater stiffness: Using longer sheaths helps bypass arterial tortuosity in regions such as the ilio-femoral arteries and improves catheter stiffness and torque transmission.

Techniques to Maximize Support

Several techniques can be used to improve the stability of the guide catheter and achieve optimal support during complex PCI procedures:

- Deep intubation: When crossing tight lesions, temporarily advancing the guide catheter for deep intubation may facilitate insertion of the device. This can be achieved by advancing the catheter over the shaft of a balloon or stent while gently rotating it counterclockwise (to align with the Left anterior descending (LAD)) or clockwise (to align with the Left circumflex (LCX) or RCA).
- Power Position Technique: For catheters such as the Ikari Left or JL, advancing the guide into the secondary curve of the aortic sinus can help to achieve the power position. However, make sure there are no proximal or ostial lesions to avoid complications.

• Buddy wire technique: Adding a second coronary wire parallel to the primary wire or into a side branch can stabilize the target vessel, create a track for device insertion, and serve as an anchor during PCI of narrow or ostial lesions [9].

Guide Extensions for Complex Cases

In recent years, guide catheter extensions have been introduced to increase the effective reach of the main catheter or to allow deeper intervention into the coronary vessel when crossing narrow or tortuous segments [10]. These extensions, which are usually 1 Fr smaller than the main catheter, help to minimize the risk of coronary vessel injury. If the proximal vessel is free of significant disease or tortuosity, the extension can be advanced deeper into the coronary artery. Alternatively, the use of an uninflated or "anchor" balloon (inchworm technique) prior to guide dilatation may help to reduce the risk of vascular injury.

Calcified Coronary Lesions Treatment

The prevalence of moderate to severe calcification is between 20–30% [11]. Calcified plaques are less compliant than lipid plaques, leading to several technical challenges such as device rupture or entrapment, difficulty in device delivery and deployment, and an increased incidence of complications such as coronary perforation and rupture [12].

In a moderate to severe calcified lesion, device compatibility with guiding catheters is critical. For example, a 6F guiding catheter is compatible with intravascular lithotripsy (IVL), orbital atherectomy (OA) and rotational atherectomy (RA) burrs up to 1.5 mm in size. However, it should be noted that the use of catheter extensions reduces the inner lumen of the guiding catheter, which limits the choice of materials that can be used.

Calcified lesions should be treated gradually. Start with less aggressive but safer devices and gradually progress to more aggressive debulking techniques, which are effective but may carry a higher risk of complications. In some cases, however, this step-by-step approach is not feasible, as certain stenoses may be impassable even with small balloons. In these cases, an aggressive approach is required from the outset, using devices that facilitate rupture of the plaque and allow passage through the stenosis (Fig. 1).

In many cases, intravascular imaging plays a crucial role as it allows better characterization of the lesion and helps in selecting the most appropriate approach on a case-by-case basis.

Balloon Based Techniques

Cutting Balloon

In less complex cases pre-dilation with a compliant or non-compliant balloon may be sufficient [13]. For more difficult lesions, pretreatment with scoring devices, such as modified balloons (e.g., cutting and scoring balloons), can significantly reduce balloon slippage, alter arterial calcification, improve stent delivery, and promote arterial compliance [14–16].

Cutting balloons (Wolverine™ Cutting Balloon™, Boston Scientific; Way Marlborough, MA 01752-1234) are particularly effective for lesion preparation, as they achieve better dilation and facilitate stent deployment by disrupting the plaque [17–19].

A cutting balloon (CB) is a non-compliant balloon equipped with three or four atherotomes (microsurgical blades) attached longitudinally to its surface. This design allows for an increase in lumen diameter at lower inflation pressures, thus reducing the risk of neointimal hyperplasia and restenosis.

According to the GLOBAL trial (a multicenter, randomized study of 1238 patients), CB angioplasty is not significantly more effective than conventional percutaneous transluminal coronary angioplasty (PTCA) in preventing restenosis in simple lesions. Instead, CB angioplasty is best suited for the treatment of more complicated lesions, where controlled dilation can achieve better immediate and long-term results than conventional PTCA. Currently, CBs are primarily used to dilate refractory, fibrocalcified plaques that are resistant to conventional high-pressure PTCA balloons, as well as to treat in-stent restenosis, ostial lesions and BL [20].

Several studies have investigated the efficacy of CB angioplasty compared to traditional balloon angioplasty. For example, the REDUCE III trial showed a lower restenosis rate (10.7%) with CB angioplasty compared to conventional PTCA (17.1%) when used before stenting. In addition, CB angioplasty has been shown to be particularly effective in small vessels (less than 2.5 mm in diameter), leading to better angiographic results and fewer serious adverse coronary events than stenting and conventional PTCA [20].

However, complications associated with the use of CB include vascular perforation (especially with oversized balloons), dissection, spasm and entrapment [21,22].

Scoring balloons, on the other hand, are semi-compliant (AngioSculpt®, Philips; NSE Alpha™, Braun) or non-compliant balloons (ScoreFlex™ NC, OrbusNeich) with flexible scoring element (usually wires or a mesh) wrapped around their surface. As the balloon inflates, the scoring element creates controlled focal disruptions or "scoring" in the vessel plaque, allowing for more precise plaque modification and improved stent deployment.

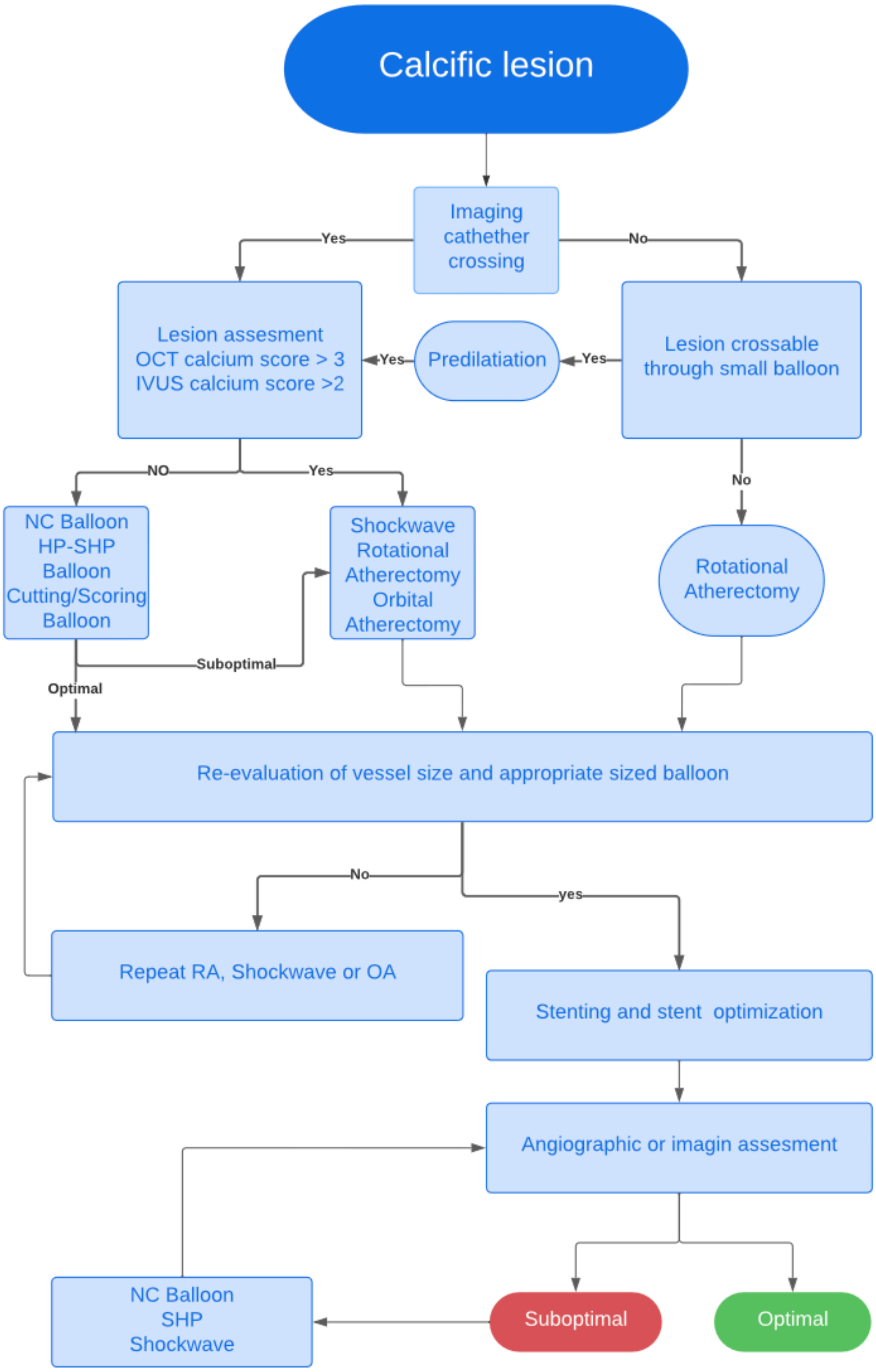

Fig. 1. Flowchart of the management of calcific lesions. OCT, optical coherence tomography; NC, non compliant; HP, high pressure; SHP, super high pressure; RA, rotational atherectomy; OA, orbital atherectomy.

However, crossability could be a limitation in the use of cutting and scoring balloons. By reducing the thickness of the blade padding, the innovative cutting balloon (Wolverine) was able to produce a low profile [23].

In calcified lesions, the novel cutting balloons showed comparable acute cross-sectional area growth and better crossability than scoring balloons.

High and Super-High Pressure Balloon

In contrast to conventional angioplasty, where the balloon is typically inflated at a lower pressure (6–10 atmospheres), in high-pressure balloon angioplasty the balloon is inflated at a pressure of over 20 atmospheres, sometimes reaching up to 30 atmospheres. While this approach can result in greater plaque modification and optimal stent expansion, it is also associated with several complications, such as vessel dissection, rupture or perforation. In addition, elastic recoil may occur in some arteries after balloon deflation, which may affect the long-term success of the procedure. A major limitation of high pressure balloons (HPB) and super high pressure balloons (SHP) is their stiffness, which can limit flexibility and increase the risk of vascular injury [17].

In the randomized ISAR-CALC trial, SHP balloons were compared with scoring balloons (OPN NC®; SIS Medical AG, Frauenfeld, Switzerland) for the dissection of calcified lesions. The results showed that both techniques achieved comparable stent expansion as assessed by intravascular imaging, highlighting the potential of scoring balloons as a less traumatic alternative in certain cases [24].

The literature shows that these balloons effectively reduce the restenosis rate, but risks such as dissections, balloon ruptures and post-PCI thrombosis remain. Short and medium-term follow-up (up to 1–3 years) is essential to monitor the safety and durability of the results [25].

Shockwave

The Shockwave Coronary IVL catheter (Shockwave Medical, Inc. Corporate Headquarters 5403 Betsy Ross Drive Santa Clara, CA, 95054 - USA**)** modifies heavily calcified atherosclerotic coronary lesions using a balloon-based delivery device and acoustic shock waves. This technique induces both longitudinal and circumferential calcium fractures, improves transmural vessel compliance, and facilitates stent expansion without the need for high-pressure balloon dilation (Fig. 2). Clinical studies have shown that IVL is safe, with low rates of major adverse cardiac events (MACE) both in-hospital and within one year and low rates of serious angiographic complications, and that it is effective, with high success rates and ease of use in the treatment of severely calcified coronary arteries.

The procedure consists of positioning the IVL balloon catheter over the target lesion, inflating it to 4 atm and delivering 12 IVL pulses. The balloon is available in diameters of 2.5, 3.0, 3.5 and 4.0 mm [26].

Compressive shock waves with peak acoustic pressures of approximately 50 atm are generated by the spark gap discharge of the emitter and radiate outwards, while the integrated balloon restricts the formation of vapor bubbles. Both the superficial and deep calcium layers are hit by the IVL shock waves. After IVL therapy, the balloon is inflated to 6 atm before deflation. Treatment cycles continue until the balloon is fully expanded (up to 80 pulses per balloon or 120 pulses with the new C2+ Generation Shockwave System) [27].

One challenge with the IVL balloon is its shape and crossing profile, which can make delivery difficult. To avoid this, pre-dilation with a low-profile balloon can be helpful, and the use of a guide extension catheter can facilitate navigation in highly stenotic and tortuous lesions. The limited length of the IVL balloon (12 mm) also makes it necessary to inflate it in multiple segments to effectively modify diffusely affected, calcified lesions. The number of runs required depends on the thickness of the calcification [28].

Unlike high-pressure balloon angioplasty or atherectomy, IVL does not apply excessive force to the arterial walls, minimizing the risk of dissection, perforation or spasm. In addition, IVL does not produce particulate deposits or emboli of plaque material.

Despite its benefits, the scientific literature points to some limitations and challenges associated with its use. First, in very deep calcifications, the energy generated may not be sufficient to disrupt the inner layers of calcification.

IVL requires a minimum lumen size for placement of the catheter and inflation of the balloon. For this reason, small vessels (<2.5 mm) may not be adequately treated due to the size of the device.

IVL technology is relatively expensive compared to other lesion preparation techniques, such as balloon cutting/scoring, which may limit its use, especially in resource-limited settings. Another limitation is the operator learning curve. Proper patient selection and positioning of the device requires experience and training. Effectiveness depends on precise balloon inflation and correct energy delivery.

The Disrupt CAD I–IV studies reported excellent procedural and angiographic success rates with low MACE rates. All four studies showed comparable primary safety (freedom from MACE) and primary efficacy (procedural success without MACE) endpoints, confirming that coronary IVL is both predictable and reliable in terms of safety and efficacy [28]. However, these studies have also highlighted that nodular calcifications and small vessels remain a challenge.

In the Disrupt CAD III–IV study, patients were followed for 1 year. It showed a low rate of major adverse cardiovascular events (MACE) and high efficacy in lesion preparation for stent implantation [29].

While the initial results of IVL are promising in terms of safety and efficacy, the long-term durability compared to other modalities (e.g., rotational atherectomy) is still under investigation.

For all these reasons, careful patient selection and integration with other interventional techniques are essential to maximize the success of the procedure.

Atherectomy

Atherectomy is an important technique in calcified lesions, not only to allow better stent expansion, but in some cases also to facilitate the crossing of particularly tight stenoses.

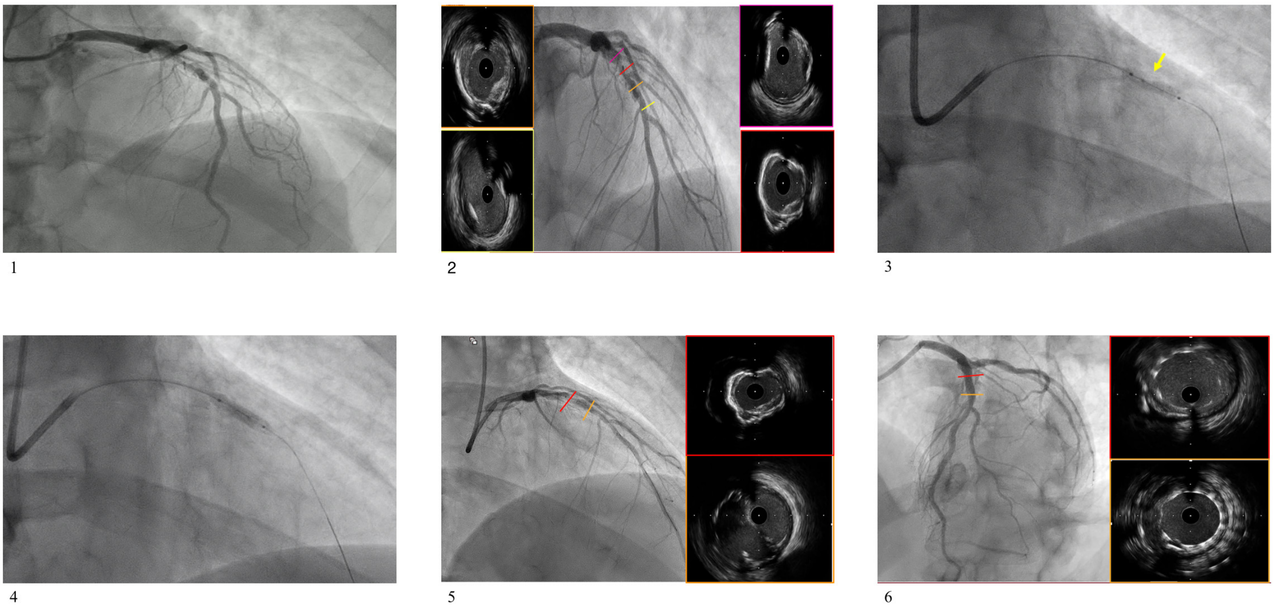

Fig. 2. IVUS-guided treatment of calcific lesions in mid segment of left anterior descending coronary artery using intravascular lithotripsy. (1) Intravascular ultrasound (IVUS) images of mid-proximal left anterior descending artery (LAD) calcific lesions; (2) Suboptimal expansion of a NC balloon; (3) Shockwave with a 3.0 × 12 mm balloon; (4) Arteriography and IVUS post-shockwave; (5) Arteriography and IVUS post-stenting; (6) Arteriography and IVUS post-stenting. The arrow, suboptimal expantion of balloon for severe calcification. The arrow, suboptimal expantion of balloon for severe calcification.

Rotational Atherectomy

Rotational atherectomy (RA Boston Scientific; Way Marlborough, MA 01752-1234) is a rotating burr with a small crystal at its distal end with a diameter between 1.25 and 2.5 mm. A ≤2.0 mm burr can be accommodated by a 7 Fr guide catheter, while a ≤1.75 mm burr can be accommodated by a 6 Fr guide catheter. An 8 Fr guide catheter is required fora burr of at least 2.15 mm [30].

Rotational atherectomy (RA) is performed with a special guide wire, which is available in two different versions: as a floppy wire (ROTAWIRE Drive floppy, Boston Scientific) and with an extra support (ROTAWIRE extra support, Boston Scientific) [12].

Crucially, RA is used for restricted (as opposed to aggressive) debulking (burr/artery ratio <0.7) because it creates a polished channel that allows for sufficient balloon dilatation, calcium fracture, and ideal stent expansion (Fig. 3). A small OCT study showed that more calcium is removed at speeds <150,000 rpm, although the recommended rotablation speed is between 135,000 and 180,000 rpm [31,32].

It is important to know when you should use RA. According to data from the ROTAXUS (Rotational Atherectomy Prior to TAXUS Stent Treatment for Complex Native Coronary Artery Disease) and PREPARE-CALC (Comparison of Strategies to PREPARE Severe CALCified Coronary Lesions) trials, RA prior to stent implantation is both feasible and beneficial in almost all patients with severely calcified lesions [33,34]. In cases where it is possible to cross the stenosis with balloons, RA may be used as a secondary option when non-compliant balloons, cutting balloons or lithotripsy are not effective, or it may be the first option in cases where stenoses cannot be crossed by other tools [12].

When using this type of material, it is important to be aware of the potential complications and how to prevent them [35]. The most common complication (5–20%) is slow flow. Appropriate burr size, brief ablation time, and gentle manipulation—without excessive speed reduction—are crucial to prevent slow flow and reduce the amount of debris produced by the RA. In addition, maintaining an adequate systolic blood pressure of 120 mmHg (minimum 100 mmHg) is critical. Adequate hydration is critical even if the patient's heart function is normal [30].

The most dangerous side effect of RA is coronary perforation caused by the burr, which occurs in 1 to 2% of cases [36].

The characteristics of the lesion, such as the vascular tortuosity or the eccentricity of the calcification, have a considerable influence on the probability of perforatio. The ellipsoidal shape of each burr makes it impossible for the RA burr to follow the highly angulated vessel, which increases the risk of perforation [37].

Eccentric calcification, such as calcified nodules, is often associated with a higher risk of perforation than concentric calcification, such as napkin ring calcification [30].

Another complication that can occur is burr entrapement. The incidence is between 0.4% and 0.8%, based on

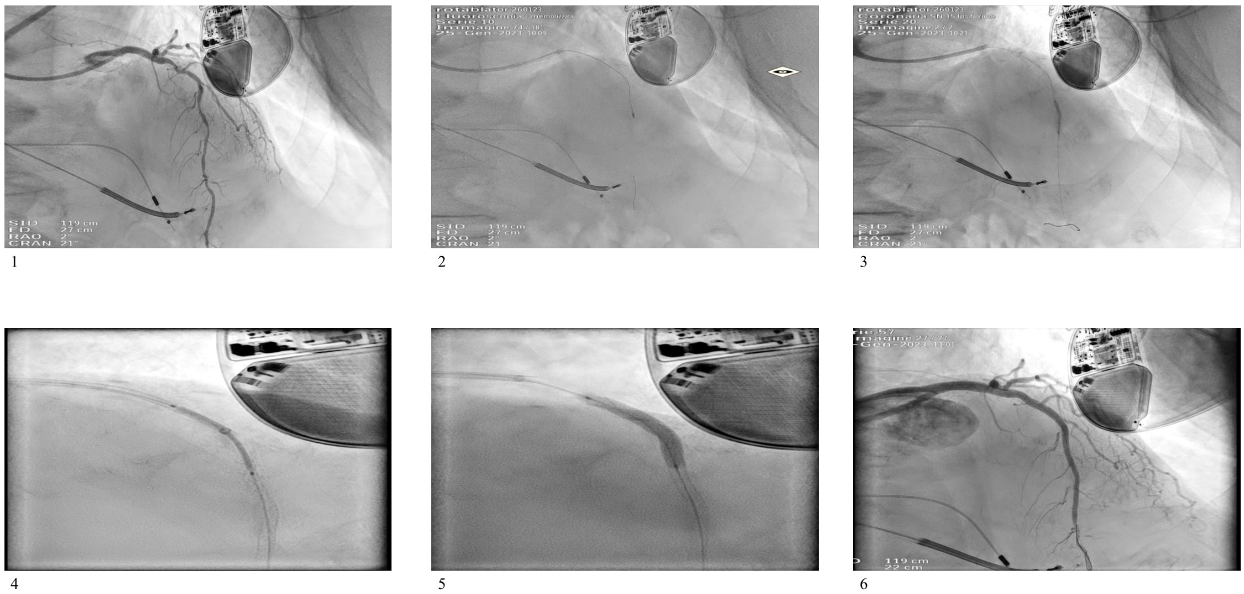

Fig. 3. Treatment of calcific lesions in mid-proximal segment of left anterior descending coronary artery using Rotational Artherecthomy. (1) Diffuse calcific disease in the mid-proximal segment of the left anterior descending artery; (2) Advancement of the rotablator on the rotawire; (3) Predilation of the lesions with a non-compliant balloon; (4) Use of extension guides to facilitate stent advancement in the mid-segment; (5) Expansion and release of the drug-eluting stent; (6) Final angiography.

single center studies rather than multicenter registries [38]. Burr entrapment can occur for various reasons. One of these is the so-called "Kokesi phenomenon", where the burr gets stuck in the distal section of the proximal constriction [39].

Another possibility is entrapment of the burr in conjunction with angulation of the vessel. Operators must be mindful of resistance, sound of ablation, and rotating speed reduction when manipulating burrs to avoid burr entrapment [30].

Despite its effectiveness in calcified lesions, this technique has certain limitations that are well documented in the scientific literature.

Rotational atherectomy requires a steep learning curve. Less experienced operators may be faced with higher complication rates. Improper use may increase the risk of complications such as dissection or perforation.

The Rotaxus trial investigated the efficacy of rotational atherectomy compared to standard balloon predilatation prior to implantation of paclitaxel-eluting stents in complex calcified coronary lesions [40]. In the study, 240 patients were randomized into two groups: one group was treated with RA followed by stenting, the other with high-pressure balloon predilatation followed by stenting. The RA group had a higher treatment success rate compared to the control group. At 9 months and at two years, the rates of major adverse cardiovascular events (MACE), target vessel revascularization (TVR) and target lesion revascularization (TLR) were similar between the two groups. The study showed that rotational atherectomy facilitates lesion preparation and improves treatment success, but does not lead to a significant improvement in long-term clinical outcomes compared to standard balloon predilatation [33].

Orbital Atherectomy

In order to reduce the calcified plaque, OA (Cardiovascular Systems, Inc., St. Paul, MN, USA) employs a differential sanding technique [41].

An eccentrically placed drive shaft with a diamond-coated crown is used to modify the plaque and increase lumen size and compliance. A special 0.014-inch guide wire (VIPERWIRE, Abbott Cardiovascular, 5050 Nathan Lane North, Plymouth, MN 55442) is used for orbital atherectomy. In contrast to RA, a single crown is used for OA. When a high rotational speed is selected, the orbital diameter expands radially due to centrifugal force. The bidirectional nature of OA, which removes plaque as it advances and retracts, is a key feature. Orbital atherectomy has been shown to alter the compliance and shape of the calcified plaque, which ultimately facilitates stent expansion [42].

There are two speed settings on the OA device. The first pass should be at a low speed (80,000 rpm); only a few lesions require a high speed (120,000 rpm). High speed should be avoided in tortuosity, severe angulation, and vessels smaller than 3.0 mm, as it may be associated with a higher risk of vessel perforation [43]. It should only be used for larger straight vessel segments if sufficient ablation or change in compliance has not been achieved after two or more passes at low speed [12].

With an efficacy endpoint of 88.9%, the ORBIT II study rated the OA system as a safe and effective technique. In addition, there were low rates of in-hospital problems (<1% each) and high rates of effective stent delivery (97.7%) [44]. Acute MI, stroke, perforation, dissection, or thrombus were all considered MACEs in this study. 10.4% for the 30-day MACE and 16.4% for the 12-month MACE were evaluated [45].

Excimer Laser Coronary Atherectomy

The basis of excimer laser coronary angioplasty (ELCA) is the emission of monochromatic coherent light with a wavelength of 308 nm in the ultraviolet spectrum, which can break chemical bonds and ablate inorganic material. Laser therapy may be helpful for calcified lesions [46], either alone or in conjunction with or following unsuccessful RA, although it is believed to be more effective for thrombi and other soft or fibrotic plaques [47]. Underexpanded stents are another particular instance where a laser can be turned on during slow contrast infusion (although there is currently no safety evidence and the indication is off-label) [48].

Intravascular Imaging

Intravascular imaging, which can detect the presence, extent and distribution of coronary calcification, provides prognostic data that can help in the planning of PCI. It can also determine whether the calcification is nodular, superficial or deep [12].

Intravascular imaging provides more sensitive and accurate information, although calcium is often described radiologically as radiopacities without cardiac motion, typically on either side of the arterial lumen, prior to contrast administration [49,50].

When it comes to accurately determining the presence and amount of deep calcium and providing quantitative indices, Optimal coherence tomography (OCT) imaging outperforms intravascular ultrasonography [51]. The likelihood that a stent will subsequently expand increases with the calcium arc or angle, length or thickness of the calcium [52,53].

Each phase of complex PCI, including baseline, lesion preparation and stent deployment, can be guided by intravascular imaging, which can also confirm the ideal stent expansion and help select the best method of calcium matching. Calcium can be assessed both cross-sectionally and longitudinally with intravascular ultrasound (IVUS) and OCT [12].

The OCT calcium score [calcium arc >180° (2 points), length >5 mm and thickness >0.5 mm (1 point each)] and the IVUS calcium score [circumferential calcium 360°, calcium >270° with a length of more than 5 mm, vessel diameter <3.5 mm and calcified nodule (1 point each)] can be used to determine the calcium burden of the lesion [12].

The use of an adjunctive device (such as RA, OA, and IVL) should be considered when a stenosis meets the criteria of high calcification (OCT calcification score >3 or IVUS calcification score ≥2) with significant luminal narrowing [54].

Less aggressive debulking techniques (e.g., NC balloons or cutting balloons) can be used in lesions with lower calcification burden, and RA or IVL should only be used if these techniques prove ineffective.

After plaque modification, intravascular imaging may be performed again and a stent deployed if calcific fracture and/or sufficient lumen dilatation is detected. According to the EAPCI consensus guidelines, correct stent expansion can be verified by post-stent intravascular imaging [12].

Although intravascular imaging is very useful in selecting the treatment approach for calcified lesions, there are some limitations to this technique. The first drawback is the cost. Nevertheless, certain meta-analyzes have shown that IVUS guidance was widely used and economical, especially in patients with complicated lesions such as LMCA or comorbidities [55]. In addition, IVUS and OCT guidance for PCI is classified as class 2a (level of evidence) according to the guidelines: According to the published rationale, most randomized clinical trials examining the use of IVUS in difficult lesions (long lesions, chronic complete occlusions, and left main lesions) were small and lacked power to assess clinical objectives. IVUS-guided PCI has been associated with less severe adverse clinical outcomes in long lesions, chronic complete occlusions, or left main artery stenting, as demonstrated by several of these studies [56]. Finally, visual interpretation is not intuitive, and guidance is difficult. IVI requires knowledge of artifacts, limitations, and confounding factors, as well as what is important and what should be ignored [56].

Bifurcations

Bifurcation lesions account for approximately 15–20% of all coronary lesions and are associated with a higher risk of complications during treatment [56,57]. Several techniques have been described to effectively treat “true bifurcation lesions” while ensuring adequate side branch (SB) intervention.

Currently, the “step-by-step” provisional stenting technique is the most widely used method to treat bifurcation lesions, as it is the simplest and has shown the best results in terms of long-term outcomes and reduced procedural complications [58]. Mastery of these techniques is critical as up to 18% of side branches can be closed in the treatment of bifurcation lesions. Over the years, there has been considerable debate about routine SB intervention, and results in the literature have been mixed. Since 2015, efforts have focused on identifying specific scenarios in which mandatory SB intervention is necessary, especially when SB is considered significant, to avoid complications such as plaque or carina displacement or, in the worst case, complete occlusion. According to experts such as Y. Louvard and A. Medina, a significant SB is one that should not be lost in light of the patient's overall clinical context, such as symptoms, site of ischemia, role of the branch in symptom development or ischemia, viability, collateral supply, and left ventricular function [59]. Recently, the definition of SB significance has been refined such that a significant SB is a vessel with a diameter ≥2.0 mm that supplies a myocardial territory accounting for at least 10% of the myocardial mass [60]. Mastery of these techniques is critical, as up to 18% of side branches can be occluded when treating bifurcation lesions. Over the years, there has been considerable debate about routine SB intervention, and findings in the literature have been mixed.

To effectively approach the treatment of bifurcation lesions, it is crucial to carefully assess plaque extension and distribution, plaque morphology and calcification, and the bifurcation angle to anticipate and evaluate the risk of SB occlusion during a main branch (MB) intervention.

During PCI at a bifurcation, it is always recommended to insert a second wire into the SB, as suggested by data from the COBIS (Coronary Bifurcation Stenting) III registry [59]. This helps to keep the SB open and allows quick access to the vessel if rewiring becomes difficult [60]. In addition, the second wire acts as a buddy wire during MB treatment, assisting in crossing MB lesions and anchoring the guide catheter, thus aiding the entire procedure. In some cases, SB wiring can be challenging due to the severity of the stenosis and the bifurcation geometry (angle). Initially, it is often sufficient to shape the curve of the wire tip to match the angle of the SB origin [60]. If necessary, the reverse wiring technique can be attempted, where the wire tip is shaped into a loop in the distal MB with a second bend that engages the SB when the wire is pulled back [61].

However, despite these techniques, rewiring the SB can sometimes be unsuccessful, especially in cases where the SB originates at an angle between 90 and 120 degrees. To overcome these challenges, several tools have been developed to facilitate rewiring.

In particular, microcatheters have proven valuable in difficult SB approaches, especially when an unfavorable bifurcation angle is present [62]. These devices provide better support by increasing pushing force and helping the guidewire to cross lesions more effectively [60]. In addition, their unique shape allows precise positioning of the guidewire in front of the SB ostium. Most microcatheters are compatible with standard 0.014-inch guidewires and have a hydrophilic coating to improve maneuverability.

Among these, the dual-lumen microcatheter is one of the most commonly used in bifurcation lesion (BL) procedures [63]. It can be easily advanced on the MB wire using a monorail system, and its dedicated channel for the SB wire allows the operator to precisely align it with the SB ostium.

A notable subset of microcatheters includes angulated microcatheters. These devices have an angled tip and are available with different degrees of angulation to accommodate various bifurcation anatomies (Fig. 4). However, they can be more aggressive on the vessel because the angled tip must be rotated within or near the stenosis to position the wire directly in front of the SB ostium.

Finally, there is the option of using a microcatheter with a deflectable tip. This tool features a distal tip that can be deflected up to 90°. The microcatheter is advanced in a straight configuration up to the bifurcation, where the tip can then be adjusted to the desired angle, allowing precise control for access to difficult side branches.

After deploying the MB stent, if intervention on the SB is required, rewiring can become even more challenging due to the presence of stent struts covering the SB ostium. In such cases, it is recommended to first perform the proximal optimization technique (POT), in which a larger balloon is used in the proximal part of the stent up to the carina of the bifurcation [60]. This helps to correct any misalignment of the stent in the proximal MB, which could otherwise make rewiring of the SB more difficult.

Once the MB stenting and POT are complete, the next step is to attempt to rewire the SB with a third guidewire through the stent struts. This process can still be challenging due to the anatomy of the bifurcation, the severity of the SB lesion, and the changes caused by the MB stenting. The previously described techniques and tools for SB base wiring can also be used to facilitate rewiring.

If the rewiring fails, the first step is to perform another POT to ensure proper expansion of the stent struts. If this is not sufficient and a significant SB was occluded during MB treatment, a rescue technique may be required. A small balloon can be advanced over the jailed SB wire to widen the access and re-establish access to the SB [64].

Recently, an "active SB protection technique" has been proposed as an alternative approach. In this technique, a balloon is preemptively positioned in the SB prior to MB stenting, as demonstrated in the CIT-RESOLVE trial [65]. In the study, this technique proved to be superior to the conventional strategy, as the incidence of SB occlusion was significantly lower, although a subgroup analysis showed no significant difference in the MACE rate at 1 year [66]. The balloon is jailed by the stent, and if the SB remains open after MB stenting, the balloon can be removed. However, if the SB ostium is compromised, the jailed balloon can be inflated to reopen access to the SB.

Another possible approach is to inflate the SB balloon at low pressure during the deployment of the MB stent. The SB balloon can then be removed and the balloon of the MB stent re-inflated to correct any proximal malposition.

Once the SB rewiring has been successfully completed, the provisional stenting technique can be continued. In most BLs, the kissing balloon (KB) technique serves as the final and safe step of the procedure [60,67]. The 5-year

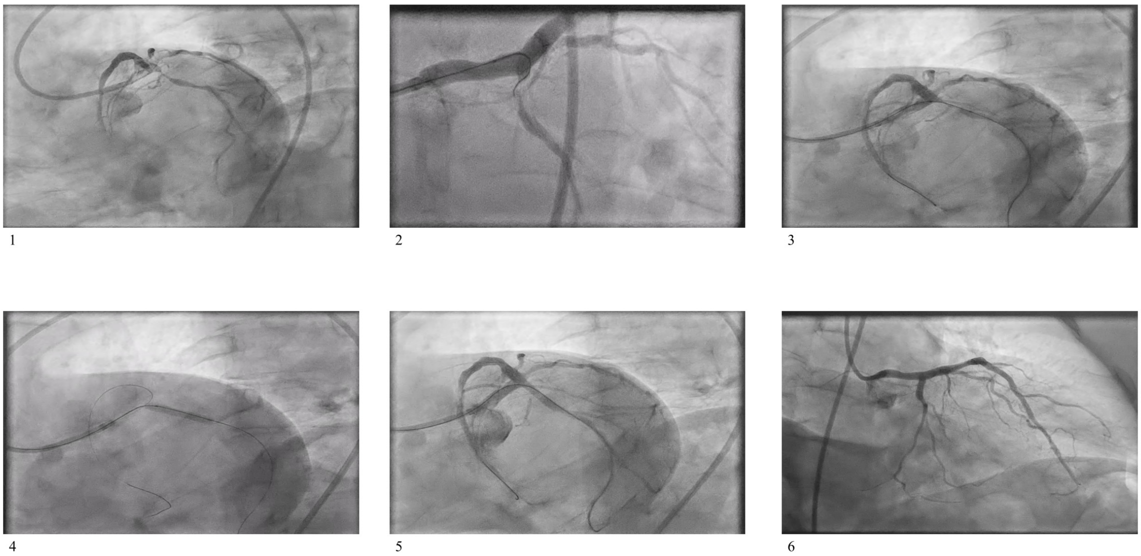

Fig. 4. Wiring of circumflex coronary artery using angulated microcatheter with a 90° angle tip. (1) Subocclusive stenosis of the proximal segment of circumflex artery that originates at a night angle from the left main; (2) Wiring the artery using angulated microcatheter after many attempts with different guide wires; (3) Advancement and expansion of the balloon through the stenosis; (4) Stent release; (5) Final angiography with the guide wire; (6) Final result.

follow-up data from the EBC-TWO trial comparing provisional stenting with culotte stenting showed that favorable procedural and clinical outcomes were achieved with KB alone, with SB stent placement required in only 16% of cases [68]. KB as the final step of provisional stenting minimizes complications associated with SB stenting, and this approach has been shown to be particularly beneficial in SB lesions less than 10 mm.

As shown in several trial such as OCTOBER and ULTIMATE, intravascular imaging techniques such as IVUS and OCT are invaluable for interventional cardiologists in selecting the optimal strategy for the treatment of BL [68,69]. Studies have shown that the use of intravascular imaging to guide BL PCI significantly reduces the rate of future adverse events compared to angiography alone (ESC Guideline 2024—Class I A recommendation) [5]. These imaging techniques help to select appropriate stent and balloon sizes, identify side branches at higher risk of occlusion and detect stent misplacement or underexpansion. Given their significant potential, we encourage interventional cardiologists to use OCT and IVUS during BL treatment to optimize outcomes whenever these tools are available. It is well known that imaging-guided PCI is significantly more expensive than angioguided procedures, but the overall cost in long-term patient outcomes can be expected to be lower due to fewer adverse events.

Conclusions

Technological advances play a critical role in supporting interventional cardiologists during complex PCI, including challenging CL and BL scenarios. The continuous development of innovative devices enhances the success of the procedure and improves patient outcomes. It is imperative for cath lab professionals to stay abreast of new technologies and effectively incorporate these tools into their practice.

Abbreviations

CL, Calcific lesions; BL, Bifurcation lesions; IVI, intravascular imaging; CAD, Coronary artery disease; PCI, Percutaneous coronary intervention; CCS, Cronic coronary sindromes; CTO, Coronary total occlusion; JL, Judkins left; AL, Amplatz left; IVL, Intravascular lithotripsy; OA, Orbital atherectomy; RA, Rotational atherectomy; CB, Cutting Balloon; PTCA, Percutaneous transluminal coronary angioplasty; HPB, High pressure balloon; SHP, Super high pressure; MACE, Major adverse cardiac events; ELCA, Excimer laser coronary angioplasty; OCT, Optical coherence tomography; IVUS, Intravascular ultrasound; SB, Side branch; MB, Main branch; POT, Proximal optimization technique; KB, Kissing balloon.

Availability of Data and Materials

Not applicable.

Author Contributions

AT and EB contributed in the manuscript writing, conception, design and review; GM, MR, AC and FD contributed in the manuscript writing and performed data acquisition; SR, MC, FG and AB contributed in the manuscript writing, provided help and advice on topics selection and review. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

We confirm that the patients had been informed about the use of these images and they allowed it.

Acknowledgment

We would like to acknowledge the important work of our cath lab equipe. We would like to thank the nurse staff and the radiologist technicians for helping us in our everyday working routine and in emergencies instances.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

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