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Review

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From single debulking techniques to combined approaches: a review of bailout strategies in heavily calcified coronary lesions

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Abstract

The increase in the average age of the population leads to an inevitable increase in demand for coronary intervention in elderly patients with more comorbidities, often carriers of coronary calcifications. Calcific lesions present a major challenge in Percutaneous Coronary Interventions, often requiring debulking techniques for successful lesion preparation. In some cases, the combined use of "dedicated" devices is essential. Some imaging-based algorithms have been established to guide the stepwise treatment of severe angiographic calcification by evaluating the calcium burden in terms of its circumferential extension, length, and thickness. Mild angiographic calcifications do not require an atherectomy strategy. Moderate and severe angiographic calcifications generally require debulking techniques. Currently, practice guidelines recommend the use of rotational atherectomy to prepare heavily calcified lesions that cannot be crossed using a balloon or adequately dilated before planned stenting (bailout situations). However, the evaluation of the plaques, as well as the characteristics of the patient, should be considered when choosing the most appropriate debulking system, and sometimes a combination of different techniques may be necessary. Therefore, understanding the various debulking systems and the possible combinations of these can be crucial for optimizing the procedural outcome.

Keywords: Percutaneous coronary interventions, calcific lesions, rotablator system, orbital atherectomy, intravascular lithotripsy system, excimer laser coronary atherectomy

INTRODUCTION

The composition of coronary atherosclerotic plaques is variable, with fibrotic and necrotic tissue, lipids, and calcium coexisting in differing proportions. Lipid-rich plaques are potentially unstable and more prone to rupture, while fibro-calcific plaques are generally more stable and typically responsible for exertional angina[1]. Advanced age, chronic kidney disease, smoking, hypertension, and diabetes have all been associated with coronary artery calcifications. The increase in the average age of the population leads to the inevitable increase of requests for coronary intervention in elderly patients with more comorbidities, often carriers of coronary calcifications. Calcific lesions present a challenging scenario for Percutaneous Coronary Interventions (PCI), as they are associated with suboptimal stent expansion and consequently an increased high risk of stent thrombosis and in-stent restenosis[2]. Moreover, severely calcified coronary lesions are related to delayed vascular healing following the implantation of new-generation drug-eluting stents[3]. While coronary artery calcium is a well-established marker of atherosclerotic burden, its relationship with plaque susceptibility to thrombotic events remains not fully understood[4]. Coronary artery calcium (CAC) scoring is a strong anatomical marker of atherosclerotic plaque burden. Studies have shown a clear correlation between CAC area and plaque volume, though not with lumen narrowing. CAC provides significant predictive value for cardiovascular risk across a wide range of populations, including younger adults, the elderly, diabetics, and smokers. It has consistently emerged as one of the most powerful predictors of coronary heart disease coronary heart disease (CHD) and atherosclerotic cardiovascular disease (ASCVD). While formal CAC scoring requires gated computed tomography (CT), qualitative assessments from routine non-contrast chest CT scans (none, mild, moderate, severe) have been shown to closely align with standard CAC categories. Recent guidelines from the Society of Cardiovascular Computed Tomography (SCCT) now recommend at least qualitative CAC assessment on all non-contrast chest CTs (Class I indication), and support CAC testing (Class II) for individuals with intermediate ASCVD risk (5%-20%) or lower-risk individuals with strong risk factors, such as a family history of premature coronary disease[4].

Patients with calcified lesions experience higher rates of target vessel failure, cardiac death, target vessel myocardial infarction, and definite stent thrombosis, demonstrating that such lesions represent an independent negative prognostic factor, regardless of clinical presentation or the type of drug-eluting stent (DES) implanted[5,6]. Balloon angioplasty in these lesions may not only result in suboptimal outcomes but also increase the risk of complications such as dissection and vessel rupture, as the balloon can stretch the non-calcified wall without effectively modifying the calcified plaque in eccentric lesions. In such cases, debulking techniques are often necessary for successful lesion preparation, and the combined use of "dedicated" devices may be critical to procedural success. In patients with severely calcified lesions undergoing DES implantation, lesion preparation with rotational atherectomy or super high-pressure and modified balloons (cutting/scoring) has been associated with comparable stent expansion. While super high-pressure balloon angioplasty is linked to improved stent symmetry, rotational atherectomy is more frequently associated with overall procedural success[7].

METHODS

The aim of this review is to summarize current evidence on debulking techniques for the treatment of heavily calcified coronary lesions, with a focus on both single-device approaches and hybrid strategies that may enhance procedural outcomes.

The search strategy included relevant controlled vocabulary and keywords related to "calcified coronary lesions", "Rotational Atherectomy", "Rotabletor", "Intravascular Lithotripsy", "Shockwave", "Orbital Atherectomy", and "Excimer Laser Coronary Atherectomy". Literature searches were conducted using PubMed and Scopus. Only studies published in English were considered.

TREATMENT ALGORITHM

Some imaging-based algorithms have been established to guide the stepwise treatment of heavily calcified vascular disease by evaluating the calcium burden in terms of its circumferential extension, length, and thickness. Mild angiographic calcifications do not require an atherectomy strategy: non-compliant (NC) or scoring/cutting balloons are often enough to obtain a good dilation of the stenosis. Atherectomy or lithotripsy should be considered only if these balloon-based strategies fail. Moderate and severe angiographic calcifications require intravascular imaging to guide further treatment strategy[8]. Intravascular imaging techniques, including Optical Coherence Tomography (OCT) and Intravascular Ultrasound (IVUS), play an essential role in the management of calcified lesions. They provide essential information about localization, thickness, and extension of calcium deposits, enable accurate measurement of vessel diameters for stent sizing, and assist in selecting the most appropriate procedural strategy[9-12].

OCT-guided or IVUS-guided procedures are associated with better stent expansion or clinical outcomes. Although intravascular imaging can guide the selection of the most appropriate technique, crossing the lesion with an imaging catheter may not be feasible in certain cases before plaque modification[13].

OCT-guided rotational atherectomy procedures for the treatment of calcified lesions result in significantly greater stent expansion compared to IVUS-guided rotational atherectomy (RA)[14].

Sometimes, the stenosis does not even enable valid imaging because of the impossibility of being crossed by imaging catheters (IVUS maximum size 3,5 French, OCT 2,7 French). In such cases, a first attempt to dilate the lesion with an NC balloon to enable imaging should be made; when it fails, a direct debulking strategy should be preferred as a first approach with atherectomy or photoablation laser. Once the morphology of vessel disease has been probed, the use of particular balloons (NC, OPN, or Cutting/Scoring balloon) can be considered only when the calcium arch is < 180° or even if the arch is > 180°, calcification thickness is < 0.5 mm, and length < 5 mm. A recent retrospective trial aimed at developing an OCT calcium score showed that coronary stenosis with a calcium arch > 180° or thickness > 0.5 mm or length > 5 mm is associated with a greater risk of stent underexpansion[15]. When any of these three parameters are present, the localization of calcium in the vessel wall becomes a critical factor - specifically, whether the calcification is deep within the media or more superficial in the intima. In the former case, intravascular lithotripsy may be considered a first-line approach: it is valid in fracturing deep calcifications, particularly when the luminal stenosis degree is not severe. In the latter case, atherectomy is generally recommended: lithotripsy balloons often rupture upon contact with the irregular, heavily calcified intimal surface. For the same reason, the presence of nodular calcifications should initially prompt consideration of atherectomy. According to a recent expert consensus document, a calcified plaque with a maximum angle > 180° and thickness > 0.5 mm should be treated with aggressive lesion preparation using atherectomy devices. Once the plaque has been "prepared" with the best strategy, the result should be checked through follow-up imaging to confirm the presence of the calcium fractures or, at the very least, luminal gain in the vessel.

The final step in the procedure is the verification of the correct and optimal expansion of the non-compliant balloon prior to the implantation of the stent. This ensures that the vessel is adequately prepared and that the stent will be effectively deployed for optimal results; a failure balloon test with an underexpanded balloon or a dog bone image must lead to repeating and increasing the preparation procedure. In some cases, the calcium layer could be both superficial and deep, so the use of both atherectomy and lithotripsy may be necessary. If stent optimization is required, it can be achieved with a NC balloon or super-high-pressure balloons (OPN) (SIS Medical AG). Optimization of a newly implanted stent using a lithotripsy balloon may also be feasible, as it can modify residual calcific elements beneath the stent struts, although this remains an off-label technique[16]. It is unknown if shock waves could damage stent struts and polymer. There are only few case reports described in the literature, regarding the use of Intravascular Lithotripsy system (IVL) in the context of underexpanded stents both immediately after its delivery and in a staged procedure[17,18]. An in vitro study assessed the impact of IVL on the polymer coating of a DES. Scanning electron microscopy analysis revealed minor disruptions of the polymer flakes, but the overall integrity of the fluoropolymer coating remained preserved, suggesting that IVL does not significantly reduce the antiproliferative drug and may not promote in-stent restenosis[19] [Table 1].

Moreover, in these patients, the rapid adoption of novel techniques and devices has been accompanied by refinements in antithrombotic strategies and pharmacological management. Optimal medical therapy should be tailored to the patient's clinical presentation and follow established treatment guidelines. In the context of PCI for chronic coronary syndromes, recent evidence indicates that potent P2Y12 inhibitors offer no significant advantage over clopidogrel in reducing myocardial injury or improving clinical outcomes. Specifically, in the setting of RA for calcified lesions, ticagrelor did not demonstrate a reduction in periprocedural myocardial necrosis compared to clopidogrel[20-23].

Dedicated materials for PCI of calcific lesions.

Once the calcified lesion has been successfully crossed, balloon under-expansion often remains a challenge. Depending on plaque characteristics, specific types of balloons can be adopted, including NC balloons, OPN, cutting balloons, and scoring balloons. For mildly to moderately calcified stenoses with a limited calcium arc (< 90°), repeated and prolonged balloon inflations should be considered a first-line strategy. Compared to compliant balloons, NC balloons exhibit minimal expansion in volume and generate greater dilating force against the vessel wall (lesion) at a given diameter and inflation pressure[24]. High-pressure balloons, such as OPN, present twin-layer balloon construction and have been developed to reach very high pressure (35 atm) with virtually zero diameter changes and hourglass/dog-boning effect[25]. This pressure may be gradually increased up to 40-50 atm in selected cases, provided there is no eccentric calcification. The Flextome™ Cutting Balloon device is a NC balloon equipped with three longitudinally mounted micro-blades on its surface. During dilatation, these blades create controlled endovascular incisions in the vessel wall, facilitating the subsequent expansion of conventional balloons[25]. A similar mechanism is employed by the AngioSculpt® RX balloon system, which features a semi-compliant nylon balloon surrounded by three external nitinol spiral scoring wires[26-28]. Scoring balloons offer greater flexibility and improved deliverability compared to other types[29].

Rotational atherectomy (ROTABLATOR/ROTAPRO)

Despite the development of all the tools mentioned above, crossing a heavily calcified lesion might require a debulking technique, like RA. Current practice guidelines recommend RA for the preparation of heavily calcified or severely fibrotic lesions that are uncrossable by a balloon or cannot be adequately dilated prior to stent implantation, particularly in bailout situations. A planned approach is often favored by experienced

Table 1. Treatment flow chart for calcified lesions

Severity of calcification	First step		Second step		Third step
Mild Arc < 180° Thickness < 0.5 mm Length < 5 mm	NC balloon or scoring balloon		Bifurcation Deep calcium Superficial calcium	IVL/ELCA IVL/ELCA RA/OA/ELCA/IVL	Combined strategy
Moderate Arc 180°-270°, Thickness 0.5-1 mm, Length 5-10 mm	NC balloon or scoring balloon		Bifurcation Deep calcium Superficial calcium	IVL/ELCA IVL/ELCA RA/OA/ELCA/IVL	Combined strategy
Severe Arc > 270°, Thickness > 1 mm, Length > 10 mm	Bifurcation Deep calcium Superficial calcium Uncrossable	IVL/ELCA IVL/ELCA RA/OA/ELCA/IVL RA/OA/ELCA	Combined strategy		-----

The table provides a stepwise approach to the treatment of calcified coronary lesions, arranged by increasing severity. The recommended interventional strategies are based on the arc, thickness, and length of calcification, as well as lesion characteristics such as location, involvement of bifurcation, and whether the lesion is crossable. Treatment steps are outlined in sequential order: first-line, second-line, and third-line options tailored to the specific lesion profile. IVL: Intravascular lithotripsy system; OA: orbital atherectomy; RA: rotational atherectomy; ELCA: excimer laser coronary atherectomy; PCI: percutaneous coronary interventions.

interventional cardiologists when angiographic or intravascular imaging reveals appropriate lesion characteristics. This practice aligns with the current AHA/ACC/SCAI guidelines, which assign a Class 2A recommendation to the use of rotational atherectomy in such scenarios[30].

Identifying patients who may benefit from RA as the first step in PCI for calcified lesions can be aided by the use of the RotaScore, which incorporates calcification severity, lesion length, vessel tortuosity, and bifurcation involvement[31].

The current evidence on RA as a bailout strategy for heavily calcified coronary lesions is limited. While some studies suggest that RA can be safely performed in such cases, the existing data are insufficient to establish definitive guidelines. Therefore, further randomized and prospective trials are necessary to evaluate the predominant use of RA as a bailout strategy in the future[32].

Currently, the Rotablator™ and ROTAPRO™ (both from Boston Scientific Scimed, Inc., USA) are the most widely used atherectomy devices worldwide. These systems remove calcified plaque using microscopic diamond chips embedded on the surface of a rapidly rotating, olive-shaped burr[33]. The latest pedal-free Rotapro system appears to be easier to operate and offers improved safety.

The “ROTATE” multicenter registry[33] investigated in-hospital and midterm outcomes of rotational atherectomy in 1,076 patients recruited between 2002 and 2013. Patients with ST-segment elevation myocardial infarction (STEMI) within 30 days, cardiogenic shock, thrombus, or in-stent restenosis were excluded. Optimal stent expansion, defined as a final percent diameter stenosis < 20%, was obtained in 90.6% of patients, and TIMI grade 3 flow was achieved in 99% of cases. The incidence of in-hospital major adverse cardiovascular events (MACE) (defined as a composite of cardiac death, myocardial infarction (MI), clinically driven, and definite stent thrombosis) was 8,3%, most of which were periprocedural MIs. The MACE rate increased to 16.0% at 1 year and 24.9% at 2 years, driven by target vessel revascularization. RA demonstrated excellent results in improving procedural success. Dialysis dependence and stent type were identified as the major independent predictors of both in-hospital and follow-up MACE. The use of second-generation DES after RA was associated with a reduction in MACE during follow-up. However, consistent with previous trials, high rates of late lumen loss and restenosis persist during long-term follow-up, despite the introduction of newer-generation DES[34].

Another similar registry was conducted in Japan, where 252 patients treated with newer-generation DES following rotational atherectomy were enrolled. The primary endpoint of the 2-year incidence of MACE was 20%, most of which were clinically driven target lesion revascularizations (18%), despite the use of newer-generation DES. This suggests that PCI for severe calcified lesions requiring RA was still challenging despite the type of stent, because of other procedural and clinical factors affecting the long-term effectiveness: diabetes, hemodialysis, Acute coronary syndrome (ACS) presentation, small vessel diameter, and long lesion length, often all present in patients with calcified coronary lesions[35]. The ROTAXUS (Rotational Atherectomy Prior to TAXUS Stent Treatment for Complex Native Coronary Artery Disease) is a randomized study evaluating a strategy of routine RA before DES implantation in complex calcified coronary lesions. The ROTAXUS trial randomized 240 patients with complex calcified native coronary lesions to RA, followed by stenting or stenting without RA[36]. The primary endpoint was the angiographic in-stent late lumen loss (LLL) at 9 months, which is defined as the difference between the post-procedure and follow-up in-stent angiographic minimal lumen diameter. In this study, RA achieved a higher rate of strategy success, largely due to fewer crossovers and stent failures compared to modified balloons. However, at 9 months, RA showed a similar LLL when used with modern DES. Both strategies demonstrated excellent clinical outcomes, with low rates of mortality, myocardial infarction, and target vessel revascularization. The results agree with studies that highlight the importance of an intravascular ultrasound-guided intervention to offer a more appropriate lesion selection and optimal treatment choice. Further analysis of the ROTAXUS trial investigated long-term outcomes and showed no differences in 2-year MACE (defined as a composite of death, new myocardial infarction, target vessel revascularization, target lesion revascularization, stent thrombosis, in segment restenosis) between the two strategies, demonstrating similar long-term outcomes regardless of the higher in-stent LLL at 9-month angiographic follow-up[36]. The Comparison of Strategies to PREPARE Severely CALCified Coronary Lesions (PREPSRE-CALC) is the second randomized clinical trial, comparing two different strategies for calcified lesion preparation before DES implantation: 200 patients were randomized to modified balloon (MB) (cutting or scoring) or RA, followed by third-generation DES implantation[37]. The primary endpoint of acute strategy success was higher with RA (98% versus 81%, respectively), primarily driven by the delivery failure of the bulky cutting or scoring balloons. A strategy of pre-dilatation with an MB failed in almost 20% of attempts, requiring bailout rotational atherectomy to successfully complete the procedure. Surprisingly, unlike the previous trials, RA did not relate with excessive neointimal response, with a low LLL that is non-inferior compared with the control arm, and did not result in higher LLL at 9 months compared to MB, and clinical outcome was excellent with both strategies, with low mortality, MI, and target vessel revascularization rates. This observation may be explained partly by the better clinical profile of included patients, but mostly by the cotreatment after RA with a third-generation DES, which has been associated with low rates of restenosis and stent thrombosis compared to everolimus-eluting stents. Moreover, OCT was performed before lesion preparation and at the end of PCI in most treated lesions, suggesting that optimal imaging to identify lesions and patients who would benefit from planned RA is the best strategy [Table 2].

Orbital atherectomy

The Diamondback 360 Coronary Orbital Atherectomy (OA) System (Cardiovascular Systems) utilizes the elliptical movement of a single-sized (1.25 mm) crown to perform bidirectional atherectomy. This system generates a high centrifugal force and a large orbital diameter, enabling it to make deep cuts into calcific plaques.

Table 2. Overview of the evidence of debulking techniques in heavily calcified coronary lesions

Authors (year)	Main finding
Dini *et al.* (2019)[2]	Modern techniques like RA and high-pressure balloon inflation significantly improve outcomes in patients with heavily calcified coronary lesions
Rheude *et al.* (2022)[7]	RA is associated with better procedural outcomes compared to balloon-based techniques for preparing severely calcified coronary lesions
Tovar Forero *et al.* (2019)[15]	IVL is introduced as a novel treatment for stent underexpansion, proving effective in treating calcified lesions and improving stent deployment
Ali *et al.* (2020)[45]	IVL is effective for treating stent underexpansion due to severe coronary calcification, improving outcomes in PCI procedures
Nagaraja *et al.* (2020)[17]	IVL can be used effectively for stent underexpansion despite the use of rotational atherectomy, demonstrating its role in treating calcified lesions
Díaz *et al.* (2012)[24]	Extremely high-pressure dilation using new non-compliant balloons effectively improves outcomes in challenging coronary lesions, facilitating better stent expansion
Mauri *et al.*(2002)[25]	Cutting balloon angioplasty reduces restenosis rates in coronary lesions, proving its effectiveness in preventing restenosis post-PCI
Schmidt *et al.* (2016)[26]	The AngioSculpt scoring balloon demonstrates safety and efficacy in preparing complex lesions in left main interventions, as shown in the ALSTER Left Main registry
Bacmeister *et al.* (2023)[32]	Planned RA before PCI in severely calcified coronary lesions results in better plaque modification compared to unplanned atherectomy, improving procedural success
Kawamoto *et al.* (2016)[33]	RA followed by stent implantation improves in-hospital and midterm clinical outcomes in patients with calcified coronary lesions
Jinnouchi *et al.* (2015)[34]	Two-year clinical outcomes after newer-generation drug-eluting stent implantation following RA for heavily calcified lesions show good long-term results
Abdel-Wahab *et al.* (2013)[35]	High-speed RA before paclitaxel-eluting stent implantation improves clinical outcomes in complex calcified coronary lesions, as shown by the ROTAXUS trial
de Waha *et al.* (2016)[36]	Two-year clinical outcomes after high-speed RA followed by paclitaxel-eluting stent implantation demonstrate long-term benefits for patients with calcified lesions
Abdel-Wahab *et al.* (2018)[37]	High-speed RA outperforms modified balloons in treating severely calcified coronary lesions before drug-eluting stent implantation, showing superior procedural outcomes
Parikh *et al.* (2013)[38]	OA is safe and feasible for treating calcified coronary lesions, offering a viable alternative to rotational atherectomy
Chambers *et al.* (2014)[39]	The ORBIT II trial demonstrates the safety and efficacy of OA in treating de novo, severely calcified coronary lesions, providing evidence for its clinical use
Redfors *et al.* (2020)[40]	The Coronary Orbital Atherectomy System (COAST) study shows that the novel micro crown orbital atherectomy system effectively treats severe coronary lesion calcification, improving procedural outcomes
Généreux *et al.* (2022)[41]	The ECLIPSE trial design suggests that OA before drug-eluting stent implantation is effective for vessel preparation in severely calcified lesions, improving clinical outcomes
Kirtane *et al.* (2025)[42]	The ECLIPSE trial shows that OA before drug-eluting stent implantation is superior to balloon angioplasty in severely calcified coronary lesions, based on a multicenter, randomized study
Okamoto *et al.* (2025)[43]	RA versus OA for calcified coronary lesions, guided by OCT, shows comparative outcomes, with OCT guidance enhancing procedural accuracy
Hill *et al.* (2020)[47]	IVL proves effective for treating severely calcified coronary artery disease, with positive outcomes in the Disrupt CAD III trial
Sintek *et al.* (2021)[48]	ELCA is safe and effective for treating resistant coronary lesions, as shown by data from the NCDR/CATH PCI Registry
Vizzari *et al.* (2024)[49]	A contrast-enhanced excimer laser stepwise approach during PCI shows improved outcomes in the treatment of resistant coronary lesions
Cobarro *et al.* (2024)[50]	ELCA is effective in treating severely calcified lesions, challenging the traditional limits of its use
Caminiti *et al.* (2023)[51]	A systematic review and meta-analysis highlight the effectiveness of IVL in treating underexpanded coronary stents, enhancing vessel expansion
Aznaouridis *et al.* (2020)[54]	The "Rotatripsy" hybrid approach is effective for treating heavily calcified coronary lesions, improving procedural success
Jurado-Román *et al.* (2019)[55]	RotaTripsy shows promising results for treating severely calcified lesions, improving clinical outcomes
Ielasi *et al.* (2020)[56]	The "Rota-Tripsy" combined approach is successful in treating long and heavily calcified coronary lesions, improving patient outcomes
Sardella *et al.* (2023)[57]	IVL as an elective or bailout strategy following rotational atherectomy in the Rota-Shock Registry provides valuable insights into its role in complex lesions
Cui *et al.* (2024)[58]	The study compares Rota-Tripsy with step-up RA, showing that this combined approach is more effective for treating severe coronary calcification

Protty *et al.* (2021)[59]	The combined use of RA and ELCA (RASER) demonstrates good outcomes for complex coronary angioplasty in calcified lesions
Sharma *et al.* (2024)[60]	The ROTA-CUT trial shows that combining RA with cutting balloon angioplasty improves stent expansion in calcified lesions, enhancing clinical outcomes
Allali *et al.* (2022)[61]	The PREPARE-CALC-COMBO study demonstrates that combining RA with cutting balloon angioplasty is effective for severely calcified coronary lesions before stent implantation
Włodarczak *et al.* (2023)[62]	Orbital-Tripsy, combining OA with IVL, is a novel and effective bailout strategy for percutaneous coronary interventions in heavily calcified lesions
Yarusi *et al.*(2022)[63]	The first case series of combined coronary OA and IVL shows that this approach is effective for treating severely calcified coronary stenoses
Jurado-Román *et al.* (2021)[64]	ELCA and IVL for severely calcified lesions prove to be an effective treatment strategy

The table presents the main studies and their key findings concerning debulking techniques for calcified lesions. OCT: Optical coherence tomography; IVL: intravascular lithotripsy system; OA: orbital atherectomy; RA: rotational atherectomy; ELCA: excimer laser coronary atherectomy; PCI: percutaneous coronary interventions; RA: rotational atherectomy; OA: orbital atherectomy; the ALSTER Left Main registry:safety and efficacy of lesion preparation with the AngioSculpt scoring balloon in left main interventions; ROTAXUS: rotational atherectomy prior to taxus stent treatment for complex native coronary artery disease; ECLIPSE: orbital atherectomy versus balloon angioplasty before drug-eluting stent implantation in severely calcified lesions eligible for both treatment strategies; CAD: coronary artery disease; NCDR: national cardiovascular data registr; ROTA-CUT: rotational atherectomy combined with cutting balloon to optimise stent expansion in calcified lesions; PREPARE-CALC-COMBO: combined rotational atherectomy and cutting balloon angioplasty prior to drug-eluting stent implantation in severely calcified coronary lesions.

The ORBIT I was a prospective, non-randomized study that involved 50 patients and showed a cumulative major adverse cardiac event rate of 4% in-hospital, 6% at 30 days, and 8% at 6 months (one additional event of cardiac death). Complications, such as dissection and perforation, were observed in 14% of patients[38]. The ORBIT II was a prospective, multicenter, non-blinded clinical trial that enrolled 443 patients who were treated with OA. The primary safety endpoint was 89.6% freedom from 30-day major adverse cardiac events, and the primary efficacy endpoint (residual stenosis < 50% post-stent without in-hospital major adverse cardiac events) was 88.9%[39]. The Novel Micro Crown Orbital Atherectomy for Severe Lesion Calcification: Coronary Orbital Atherectomy System Study (COAST) was a prospective, multicenter, single-arm study that enrolled 100 patients with severely calcified de novo coronary lesions. Procedural success was achieved in 85.0% of subjects, while freedom from MACE was 85.0% at 30 days and 77.8% at 1 year[40]. In contrast, the Orbital Atherectomy Versus Balloon Angioplasty Before Drug-Eluting Stent Implantation in Severely Calcified Lesions Eligible For Both Treatment Strategies (ECLIPSE), a prospective randomized trial, compared routine use of OA with conventional balloon angioplasty in patients with severely calcified coronary artery lesions[41]. The primary endpoints were target vessel failure (TVF) at 1 year and minimal stent area (MSA) at the site of maximal calcification, assessed by optical coherence tomography. The study found no significant differences between the two groups, suggesting that routine OA does not offer additional benefits over balloons in this patient population[42]. The DIRO study, another prospective randomized trial, aimed to compare RA with OA. In this study, stent expansion was significantly greater in the RA group compared with the OA group (99.5% *vs*. 90.6%; P = 0.02). Additionally, the maximum atherectomy area was significantly larger in the RA group. However, procedural outcomes and clinical events at 8 months did not differ between the groups[43] [Table 2].

Intravascular Lithotripsy (SHOCKWAVE)

The IVL (Shockwave Medical) uses the same physical principle of lithotripsy for kidney stone treatment. The device consists of a portable generator, a connector cable with a push button, and a rapid-exchange, semi-compliant balloon catheter compatible with a 0.014 common guidewire. The balloon integrates two radiopaque lithotripsy emitters that deliver targeted acoustic energy to disrupt intimal and medial calcium[44]. Unlike traditional debulking techniques, IVL modifies plaque without causing direct vascular injury. The calcium fragments remain embedded within the vessel wall, thereby reducing the likelihood of distal embolization and slow-flow or no-reflow phenomenon. However, some lesions might not be suitable for shock wave treatment. Severe vessel tortuosity or angulation, critical lumen reduction, significant plaque eccentricity, or protrusion into the lumen could prevent effective calcium fracture or increase the risk of balloon rupture.

The feasibility of using IVL to modify calcific plaque in human coronary arteries was first demonstrated in the "Disrupt coronary artery disease (CAD)" study. Conducted between 2015 and 2016, the study enrolled only 60 patients, each with at least one coronary stenosis 50% and severe calcification confirmed by angiography. Clinical success, defined as the ability of IVL to produce residual diameter stenosis < 50% after stenting in the absence of in-hospital MACE, was reached in 94% of patients. "Disrupt CAD II" evaluated in 120 patients the safety and effectiveness of IVL for vessel preparation of severe calcific de novo coronary lesions before stenting; OCT was used to examine its mechanism of action and effectiveness[45]. The primary safety end point of in-hospital MACE occurred only in 5.8% of patients, consisting of 7 non-Q-wave myocardial infarctions. Clinical success (defined as the Disrupt CAD I study) was achieved in 94.2% of patients. The OCT sub-study identified calcium fracture following IVL in 78.7% of lesions, and the minimal lumen area was increased from 2.33±1.35 mmq to 6.10±2.17 mmq after DES implantation. The latest "Disrupt CAD III" was designed for U.S. regulatory approval, with an objective similar to its predecessors: to evaluate the safety and efficacy of IVL in optimizing stent deployment in patients with severely calcified de novo coronary stenoses. The mechanism of calcium modification was assessed in an OCT sub-study[46]. The primary safety endpoint (freedom from MACE at 30-day from index procedure) was achieved in 92.2% of patients. The primary efficacy endpoint (defined as in the other "Disrupt CAD" study) was achieved in 92.4% of patients. OCT after IVL identified calcium fractures in 67.4% of lesions, most of which were circumferentially distributed and observed in multiple longitudinal planes. The OCT sub-analysis demonstrated a large mean MSA post-procedure and excellent stent expansion. Notably, MSA and stent expansion were comparable regardless of whether calcium fractures were identified by OCT. Interestingly, the maximum calcium fracture width increased further following stent expansion compared to pre-expansion measurements. All these studies are non-randomized and lack a concurrent control group. Furthermore, the protocols of the three studies have excluded the use of adjunctive tools for plaque modification (atherectomy or cutting/scoring balloons) to facilitate IVL balloon crossing and avoid confounding elements. Notably, studies testing the combined use of these tools with IVL are currently lacking. It would be valuable to explore the early use of IVL after a DES implantation in cases of stent underexpansion due to previously undetected calcific stenosis. In a systematic review and meta-analysis involving 354 patients, the "stent-through" IVL plaque modification technique was shown to be a safe and effective option for treating stent underexpansion caused by calcified coronary plaque, demonstrating a high success rate and a very low incidence of complications[47] [Table 2].

Excimer laser coronary atherectomy

Excimer laser coronary atherectomy (ELCA) uses a xenon chloride excimer laser to produce bursts of ultraviolet light at 308 nm, with a pulse frequency of 25-80 Hz and a fluence of 30-80 mJ/mm (48). ELCA was initially approved by the United States Food and Drug Administration for PCI in 1992[48]. A retrospective analysis using data from the National Cardiovascular Data Registry CathPCI Registry evaluated the outcomes of ELCA. The study found that the overall complication rate associated with ELCA was significantly higher; however, in the in-stent restenosis group, the complication rate was lower (odds ratio: 0.51; 95%CI, 0.42-0.63)[48]. Another retrospective study evaluated contrast-enhanced ELCA and suggested that it is a safe and effective treatment option for managing both de novo and in-stent-resistant coronary lesions[49]. Furthermore, Cobarro *et al.* reported that ELCA was associated with a low rate of procedure-related complications and a low incidence of MACE during 1-year follow-up[50] [Table 2].

Combined use of rotational atherectomy and intravascular lithotripsy

Lithotripsy has proved very effective in fracturing both superficial and deep calcium. However, it is not always applicable as a first-line technique for two main reasons: First, the reduced luminal caliber of heavily calcific vessels, along with the endoluminal spurs, can prevent the passage of the balloon lithotripsy delivery. Second, irregularities on the luminal calcific surface caused by calcification often lead to balloon rupture. In such cases, rotational atherectomy serves as the initial treatment of choice. It ablates superficial calcium and enlarges the intraluminal space. If subsequent OCT check or "balloon testing" reveals residual deep calcium, lithotripsy can be employed to further prepare the vessel for stent implantation. These two techniques are neither mutually exclusive nor interchangeable, but are complementary. A sequential, hybrid approach is desirable in severely calcified coronary stenoses where calcium is distributed both superficially and in deeper layers. This combined approach has recently been described in the literature under terms such as "Rota-Shock" or "Rota-Tripsy"[51-56].

Sardella *et al.* evaluated the elective or bailout use of IVL following RA in patients with severe coronary artery calcification using data from the Rota-Shock Registry, which included 160 patients. The study reported a procedural success rate of 96.9% and a primary safety endpoint of 90.6%. Furthermore, 98.7% of patients were free from in-hospital major adverse cardiac and cerebrovascular events, including cardiac death, target vessel myocardial infarction, target lesion revascularization, cerebrovascular accident, definite/probable stent thrombosis, and major bleeding[57].

A recent study compared the effectiveness of the RotaTripsy approach with the step-up approach in treating severely calcified coronary lesions. Both methods yielded favorable short-term outcomes in terms of procedural success and safety. However, the RotaTripsy technique demonstrated superior performance, achieving more effective and safer treatment of challenging calcifications. This combined approach may offer distinct advantages over the step-up approach in managing complex coronary calcifications. Further studies, particularly multicenter randomized trials, are needed to validate these results and assess the long-term benefits of combining RA and IVL. Indeed, this is a retrospective study with a small sample size, including only 37 patients (18 assigned to Rota-Tripsy and 19 to the step-up approach RA). Moreover, only a single shockwave balloon was used for each patient in this study, although using two or more shockwave balloons may potentially improve the results[58] [Table 2, Figures 1 and 2].

Combined use of rotational atherectomy and excimer laser coronary atherectomy

Using data from the British Cardiac Intervention Society database, 153 patients treated with Rotational Atherectomy and Excimer Laser Coronary Atherectomy (RASER) atherectomy were identified. Although RASER plaque modification in complex PCI was associated with higher baseline risk and procedural complexity, adjusted rates of in-hospital major adverse cardiac and cerebrovascular events (MACCE) did not significantly differ from non-RASER procedures. These results suggest that RASER does not independently increase risks of MACCE, hemorrhage, or mortality[59].

Combined use of rotational atherectomy and particular balloons

The Rotational atherectomy combined with cutting balloon to optimise stent expansion in calcified lesions (ROTA-CUT) trial is a randomized controlled study aimed at assessing the safety and efficacy of lesion preparation using a combination of RA and cutting balloon versus RA followed by NC balloon in patients undergoing PCI with drug-eluting stent implantation for moderately or severely calcified lesions. In this study, which enrolled 60 patients, the minimum stent area evaluated by IVUS did not show significant differences between the two groups (6.7 ± 1.7 mm^2 *vs.* 6.9 ± 1.8 mm^2; $P = 0.685$), nor did the minimum lumen area or stent expansion. The RA followed by cutting balloon was found to be safe, with rare procedural complications and minimal clinical adverse events at 30 days, showing no significant differences

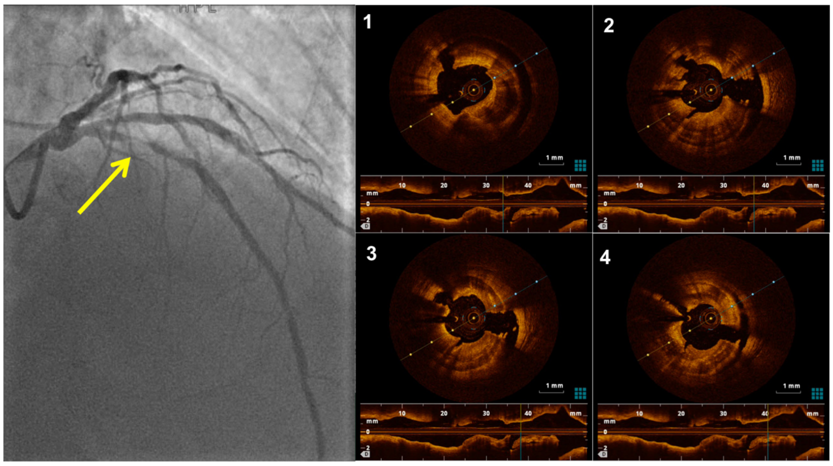

Figure 1. Left panel: Left coronary angiogram showing severe concentric stenosis in the proximal LAD (yellow arrow). Right panel: OCT images of a severely calcific concentric plaque, presenting deep radial and longitudinal (long-axis view shown below) fractures after combined treatment with Rotational Atherectomy (Rotablator) and IntraVascular Lithotripsy (Shockwave). LAD: Left anterior descending artery, OCT: optical coherence tomography.

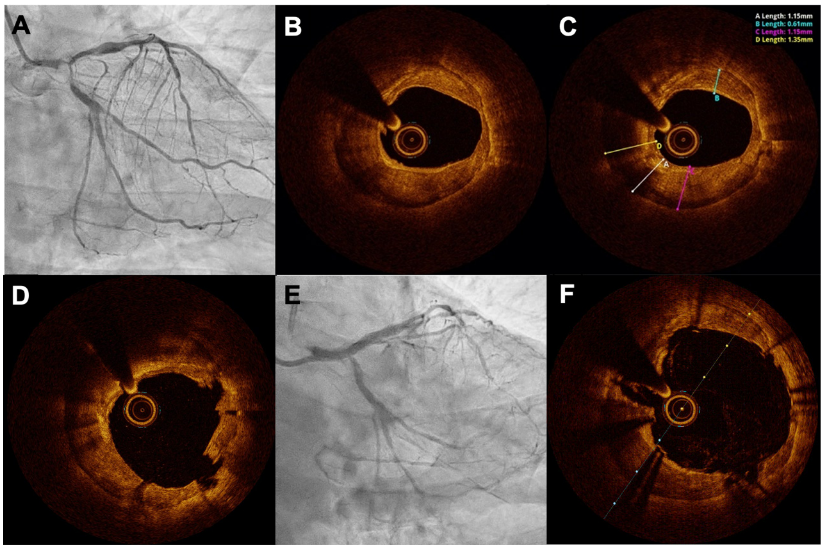

Figure 2. A 74-year-old male patient with severe calcific three-vessel disease presented with critical stenosis at the left main bifurcation (Medina 1,1,1), proximal LAD, OM2, and CTO of the mid RCA (A), who refused cardiac surgery. As the first step, OCT-guided LM PCI was performed; OCT showed severe circumferential calcification (B) with a maximum thickness of 1.35 mm (C). Due to the incomplete expansion of NC balloons (up to 3.0 mm), accompanied by a dog-bone effect, effective plaque debulking was achieved using a 1.5 mm RotaPro burr, followed by coronary lithotripsy (Shockwave 3.5 mm balloon); Subsequent OCT imaging demonstrated both circumferential and longitudinal calcium fractures (D); after stent implantation (E), OCT confirmed an optimal increase in lumen area, with excellent stent expansion and strut opposition (F). RCA: Right coronary artery; LAD: left anterior descending artery, LM: left main; PCI: percutaneous coronary intervention; OM: obtuse marginal; OCT: optical coherence tomography; NC: non-compliant balloon.

between the groups[60]. In contrast, the Combined rotational atherectomy and cutting balloon angioplasty prior to drug-eluting stent implantation in severely calcified coronary lesions (PREPARE-CALC-COMBO) trial is a single-arm prospective study that compares the Rota-Cut strategy (which combines rotational atherectomy with either a medium balloon, scoring balloon, or cutting balloon) to historical data from the randomized PREPARE-CALC trial. This trial enrolled 110 patients and demonstrated that the Rota-Cut combination led to a higher MSA of 7.1 ± 2.2 mm^2 compared to 6.1 ± 1.7 mm^2 with medium balloon and 6.2

± 1.9 mm^2 with RA alone (P = 0.003 and P = 0.004, respectively). There was one in-hospital death recorded. Target vessel failure at 9 months was low and comparable between groups (8.2% *vs.* 8% with MB *vs.* 6% with RA; P = 1 and P = 0.79, respectively)[61].

The PREPARE-CALC-COMBO study suggests that the Rota-Cut strategy may provide advantages in achieving a larger minimal stent area compared to RA or dedicated balloon therapy, although it does not improve stent expansion. Importantly, it maintains a safety profile comparable to traditional methods[61].

Combined use of orbital atherectomy and intravascular lithotripsy (ORBITAL-TRIPSY)

A case report highlighted the application of the Diamondback 360° Coronary Orbital Atherectomy System (Cardiovascular Systems Inc.) in a patient who underwent six successful low-speed atherectomy runs at 80,000 rpm, followed by four high-speed runs at 120,000 rpm. Despite these efforts, the deployment of a DES resulted in a "dog bone effect". To address this issue, shockwave intravascular lithotripsy was performed using a 3.0 × 12 mm catheter (Shockwave Medical Inc., Santa Clara, CA, US). Following 40 ultrasonic pulses, full stent expansion was achieved. In addition, a case series involving eight patients evaluated the combined use of orbital atherectomy and shockwave intravascular lithotripsy. This series reported that the combination of these two techniques was both safe and effective, leveraging their distinct yet complementary mechanisms of action. Importantly, the rates of MACE were 0% both during hospitalization and at the 30-day follow-up. However, the short follow-up period and small sample size limit conclusions about long-term safety[62,63].

Combined use of ELCA and lithotripsy (ELCA-Tripsy)

A case report described the use of a 0.9 mm ELCA catheter (80 mJ/mm^2, 80 Hz) to facilitate the delivery of a Shockwave balloon (Shockwave Medical). In this case, after 80 pulses, a DES was implanted. Optical coherence tomography revealed deep calcified plaques with fractures induced by IVL, indicating a favorable final outcome[64].

Consensus statements, controversial issues and future directions

The current consensus statement suggests that plaque modification techniques should be considered in the following cases:

• When a coronary lesion shows a high calcium score on Coronary Computed Tomography Angiography or high calcium burden with lumen narrowing, as determined by IVUS or OCT;

• If the lesion cannot be adequately dilated with a semi-compliant or NC balloon at high pressure;

• When intravascular imaging devices are unable to cross the stenosis[13].

The choice of device should consider:

• The type of lesion and its location;

• The ability to cross the lesion with a semi-compliant or high-pressure balloon;

• The presence of superficial or deep calcification, assessable through intravascular imaging;

• The need for side-branch protection in bifurcation lesions;

• The vessel size and degree of balloon or stent expansion;

• The presence of complications or difficulties in stent expansion;

• The experience of the operator;

• The available resources[31].

In cases of uncrossable lesions with standard balloons, the use of RA) or ELCA may be required. If the lesion is crossable and can be assessed with intravascular imaging (OCT or IVUS), device selection should be guided by calcium scoring: if the OCT calcium score is > 3 or the IVUS calcium score is > 2, IVL, RA, or OA should be considered. If these thresholds are not met, the use of dedicated balloon technologies may be appropriate as the initial strategy. It is important to note that in bifurcation lesions, RA, OA, and IVL should only be used when side-branch wire protection is not mandatory. OPN balloons, designed for ultra-high-pressure inflation with uniform expansion, may compromise the ability to recross the lesion. Conversely, with cutting balloon (CB), vessel perforation and blade entrapment remain the most concerning complications[13,65] [Table 1].

Regardless of the initial device selected, the need for a secondary debulking technique remains high. In the recently published ROLLER COASTR-EPIC22 trial, 10.5%-14% of patients required a combined technique, with similar usage rates observed for RA, IVL and ELCA. This likely reflects the different mechanisms of action of these devices. Notably, this was the first prospective randomized trial to compare the safety and efficacy of these debulking systems. The trial demonstrated that IVL was non-inferior to RA in terms of stent expansion, as assessed by OCT. In contrast, ELCA did not meet the criteria for non-inferiority. All three treatment arms achieved comparable procedural success rates and minimal stent areas, with a low and comparable overall complication rate. Importantly, no coronary perforations were reported in the IVL group[66].

Procedural complications in the context of calcified coronary lesions are closely related to both the complexity of the lesion and the type of debulking system used. The most common complications include:

• Coronary rupture or perforation: can occur when using RA or high-pressure balloon inflation, or occasionally with IVL. If cardiac tamponade develops, urgent pericardiocentesis may be required. Management options include: covered stent implantation, prolonged balloon inflation, or the use of embolic agents such as coils, fats, or microspheres;

• Temporary pacemaker implantation: may be necessary during rotational or orbital atherectomy (RA or OA) in PCI of the right coronary artery or a dominant left circumflex artery;

• Slow-Flow/No-Reflow Phenomenon: may result from embolization of plaque material to the distal coronary bed, microvascular dysfunction, and/or arteriolar spasm. Pharmacological treatments such as adenosine can be considered for managing this condition.

The advancement of imaging technologies offers the potential to monitor the progression of calcification morphology over time, thereby enhancing prognostic assessment in high-risk, vulnerable patients and facilitating the development of novel therapeutic strategies[67]. The emergence of AI-driven technologies may further support procedural planning by not only identifying the most appropriate debulking technique, but also enabling the design of pre-planned, combined approaches tailored to lesion characteristics. In addition, practical training in plaque modification techniques can be effectively acquired through simulation-based learning. This should include a substantial initial period of assisting as a second operator, followed by supervised procedures as the primary operator, considering that the proper device use significantly reduces the incidence of complications.

Moreover, considering the expanding indications for Transcatheter Aortic Valve Implantation (TAVI) and the strong association between severe aortic stenosis and coronary artery disease, the findings from the REVASC TAVI registry-which showed that PCI performed after TAVI is associated with better outcomes compared to other revascularization timing strategies-highlight a potential new area of interest: the use of debulking techniques in these patients. Currently, there are limited data available regarding complex PCI for heavily calcified coronary lesions in patients who have undergone TAVI[68,69].

CONCLUSION

The management of complex, heavily calcified coronary lesions requires a comprehensive understanding of the full range of debulking techniques to ensure successful PCI. The effectiveness of approaches such as rotational and orbital atherectomy, laser and shockwave lithotripsy, and specialized balloons underscores the need for a patient-specific, tailored strategy. Clinicians must not only be proficient in these individual techniques but also consider their strategic combination to optimize patient outcomes. By leveraging the unique mechanisms of each modality, operators can enhance procedural success and minimize risks, ultimately improving the management of challenging coronary lesions.

DECLARATIONS

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