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Left main bifurcation stenting: a 2023 appraisal

Implantação de stent na bifurcação do tronco da coronária esquerda: uma análise em 2023

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ABSTRACT - For several decades coronary bypass grafting has been considered the gold standard treatment for unprotected left main coronary artery lesions. However, the anatomic accessibility and the large caliber of the vessel render the percutaneous coronary intervention a very attractive treatment option for left main coronary artery lesions. The use of percutaneous coronary intervention in this subset of lesions has been further expanded as a result of the introduction of newer drug-eluting stents along with rapid advancements in techniques, devices, and adjunctive pharmacotherapies. The current evidence has demonstrated that patients with low or intermediate coronary complexity treated with percutaneous coronary intervention or coronary bypass grafting have comparable outcomes, for up to 10 years. Treatment of left main bifurcation lesions remains technically demanding despite recent developments. The provisional approach is the default strategy in most types of left main bifurcation lesions. However, a few complex left main bifurcation lesions would warrant an elective two-stent technique. An integrated approach incorporating custom-tailored techniques, adjunctive physiological and morphologic evaluation, and pharmacologic agents is critical to tackle this unique challenge and improve clinical outcomes.

Keywords: Coronary artery disease; Coronary artery grafting; Percutaneous coronary interventions; Drug-eluting stent

RESUMO - Por várias décadas, a revascularização do miocárdio foi considerada o tratamento padrão-ouro de lesões não protegidas do tronco da coronária esquerda. No entanto, a acessibilidade anatômica e o grande calibre dos vasos tornam as lesões de tronco uma opção atraente para a intervenção coronária percutânea. A aplicação dessa intervenção nesse cenário foi expandida ainda mais como resultado da introdução de novos stents farmacológicos, com rápidos avanços em técnicas, dispositivos e farmacoterapias adjuvantes. As evidências atuais têm demonstrado que pacientes com complexidade coronariana baixa ou intermediária têm desfechos similares com a intervenção coronária percutânea ou a revascularização cirúrgica do miocárdio por até 10 anos. O tratamento das lesões da bifurcação do tronco da coronária esquerda continua tecnicamente complexo, apesar dos recentes avanços. A abordagem provisional é a estratégia padrão na maioria dos tipos de lesões da bifurcação do tronco da coronária esquerda. No entanto, algumas lesões complexas da bifurcação do tronco da coronária esquerda justificariam uma técnica eletiva com implante de dois stents. A abordagem integrada, que incorpora técnicas dedicadas, uma avaliação fisiológica e anatômica adjuvante e agentes farmacológicos, é fundamental para abordar com sucesso esse desafio ímpar e melhorar os desfechos clínicos.

Descritores: Doença da artéria coronariana; Ponte de artéria coronária; Intervenção coronária percutânea; Stents farmacológicos

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INTRODUCTION

Significant unprotected left main (LM) coronary artery disease account for approximately 5 to 7% of the patients undergoing coronary angiography (CAG)[1-3], and more than 80% involve the bifurcation. Based on clinical evidence, the 2018 European practice guidelines for myocardial revascularization[4] supported LM percutaneous coronary intervention (PCI), with a class I recommendation and a level of evidence A in patients with low SYNTAX score (<22), and with a class IIa recommendation and a level of evidence A in those with intermediate SYNTAX score (23 to 32). Coronary artery bypass surgery (CABG) was recommended as the gold standard in patients with high SYNTAX Score (>32). Heart Team discussion was also recommended accordingly for more appropriate decision-making.[4] The latest American Heart Association/American College of Cardiology/Society for Cardiovascular Angiography and Interventions guidelines still favor CABG over PCI in patients with LM disease (class I – level of evidence B) independently of the location of the disease in the LM, whereas PCI is now a class IIa recommendation (level of evidence: B, for both).[5] In European Guidelines, CABG is a class I recommendation for patients with associated multivessel disease, whereas PCI is a class III recommendation. Due to the anatomical accessibility and relatively large caliber of the LM, PCI is a very attractive option for treating LM lesions.[6] Furthermore, remarkable advancements in the PCI field including device technology, PCI technique, adjunctive pharmacotherapy, and improved procedural outcome have emboldened interventional cardiologists to adopt PCI.[7] Excellent outcomes with lower mortality have been reported with PCI in ostial and mid-shaft lesions compared with LM bifurcations.[8] Lack of randomized controlled trials (RCTs) addressing the LM bifurcation has led to uncertainties regarding the optimal stenting strategy. Albeit the provisional one-stent technique is the default strategy, a straightforward two-stent technique is frequently required for complex LM bifurcation lesions.[9]

ANATOMY AND RHEOLOGY

Given its large caliber, the LM tends to have high plaque volume. Additionally, it is prone to calcification. Plaque and carina shift and incomplete stent expansion are critical technical considerations in LM bifurcation PCI. Greater elastic tissue content of this artery explains the elastic recoil and high restenosis following balloon angioplasty.[10,11] Left main represents the largest coronary bifurcation, and LM PCI techniques are driven by potential complications to the side branch (SB), normally the left circumflex (LCX) coronary artery, such as acute occlusion and long-term adverse outcomes of target vessel failure and target lesion revascularization (TLR). In the LM bifurcation, the atherosclerotic process is accelerated primarily in the area of low wall shear stress (WSS) along the lateral wall elongating distally on the myocardial walls of the left anterior descending (LAD) and LCX arteries.[12] The carina is normally spared or minimally involved. There is an interplay among flow dynamics, rheology, and geometry. The local hemodynamic factors play a crucial role in the initiation of atherogenesis and thrombosis. A long LM (≥10mm) tends to have greater pressure drop and lower WSS contributing to plaque formation.[13] A tree-dimensional computational fluid dynamics model demonstrates the development of atherosclerotic plaque at sites of bifurcation where low WSS, oscillating WSS, flow division, and stasis appear.[14] While Medina 1.0.0 bifurcation has the greatest risk of plaque proliferation, Medina 1.1.0, 1.1.1, and 1.0.1 bifurcations resist atherogenesis better due to higher average WSS.[14] The current strategy to treat the LM bifurcation by extending the main branch (MB) stent into the proximal LAD is supported by the continuous extension of the plaque from the LM to the proximal LAD artery in 90% of cases.[15] LM typically has a diameter ranging between 4.5 to 6mm in a majority of cases, whereas LAD and LCX have diameters ranging from 3.5 to 4.5mm to 3.0 to 4.5mm, respectively leading the operators to be accustomed to large diameter stents with expansion properties (Figure 1).[16]

Stent size	Xience Sierra™	Xience Alpine™	Skypoint	Synergy™	Megatron™	Onyx™	Orsiro	Orsiro Mission
2.0								
2.25		3.25				3.25		
2.5				3.5				
2.75	3.75		3.75			3.75	3.5	3.59
3.0		3.75						
3.25				4.25				
3.5	5.5	4.5				4.75	4.5	4.42
4.0			5.75	5.75	6.0			
4.5						5.75		
5.0								

Source: the authors.
Figure 1. Maximal expansion capacity with current drug-eluting stent platforms.

A wider bifurcation angle (between the LAD and the LCX) has signalled adverse outcomes after the culotte and classical crush techniques.[17-19] However, in the Double Kissing Crush versus Culotte Stenting for the Treatment of Unprotected Distal Left Main Bifurcation Lesions III (DKCRUSH-III) study, double kissing (DK) crush has reported lower rates of MACEs when the bifurcation angle between the LAD and LCX is >70° compared with the culotte stenting technique.[20] Therefore, for wider bifurcation angles or when the LCX is smaller than the LAD (but larger than 2mm), DK crush may be the ideal two-stent technique. If the bifurcation angle is less than 70° and the LCX diameter is identical to or within 0.5mm of the LAD diameter, either the culotte or the DK crush technique can be performed.[12,21] LM disease tends to be diffuse and may conceal stenosis. The diffuse nature of the disease should be suspected if the LM reference diameter is comparable to the LAD reference diameter.

WHAT IS UNIQUE ABOUT THE LEFT MAIN BIFURCATION?

The LM is the largest bifurcation of the coronary tree and has some unique specificities warranting a different technical strategy compared to other coronary bifurcations which are more distal in the coronary tree:

- The myocardium supplied by the LM generally accounts for considerably more than 50% of the total myocardial mass. Technical inadequacies may lead to a catastrophe during the procedure due to the larger myocardium in jeopardy. It may also impact the long-term outcome.
- The LM is the only bifurcation where the proximal MB originates directly from the aorta which has numerous strategic and technical implications. The ostium of the LM is a component of the aorta and is significantly more resistant than other segments of the coronary tree to the radial force provided by the stent. Indeed, cases of stent recoil requiring implantation of a second stent inside the first one have been reported.
- With a proximal reference diameter generally measuring between 4.5 and 6mm, this type of bifurcation is rather large considering the size of the currently available drug-eluting stent (DES).
- The aspect of diffuse LM disease may be misleading and cause the vessel to appear disease free.[22] The branching law principles allow the identification of diffuse LM disease when the LM reference diameter is identical to the LAD reference diameter.
- 10% of LM cases reveal trifurcations needing solid treatment strategies.[23]
- The atheroma is formed in areas opposite to the flow divider in LM bifurcation as in any other non-LM bifurcation. However, LM bifurcation has a more disseminated distribution.[14] It appears, however, that plaque distribution may influence the long-term prognosis.[24]
- Left main lesions are frequently calcified.[25] This underscores the need for various plaque modification strategies including atherectomy. The bifurcation angle is generally wider (T-shaped) in LM which could impact the prognosis after stenting.[26] Wider angle results in abbreviation in the systolic-diastolic variation of the bifurcation, which may, in turn, cause stent fracture and midterm adverse clinical events.[27] Additionally, wide bifurcation angles have been found to contain areas of high shear stress adjacent to those of low shear stress, the former possibly stimulating platelet activation and aggregation, and the latter engendering a localized milieu of stasis and thrombosis.[28,29] In conclusion, stent placement in bifurcations with >70° angles induces consequential rheological changes and may result in suboptimal stent apposition, especially when a two-stent technique is used.[30,31]
- Numerous studies have demonstrated that incomplete revascularization results in a higher risk of MACE. The residual Synergy Between ICP With Taxus and Cardiac Surgery (SYNTAX) score has highlighted the significantly increased risk associated with scores > 8.[32] This is even more pertinent in patients with LM disease in whom untreated chronic occlusion of the right coronary artery is associated with a higher mortality risk.[33,34]

CURRENT INTRACORONARY IMAGING AND PHYSIOLOGY FOR LEFT MAIN BIFURCATION LESIONS

The assessment of LM lesion by CAG is often hindered by the lack of a reference segment, lesion angulation, eccentricity, bifurcation anatomy, overlapping branches, and foreshortening.[35] The Medina classification[35,36] is an angiographic classification of the bifurcation lesion complexity, which defines plaque distribution and procedural planning but does not prognosticate PCI outcomes. Several parameters (including larger SB, long SB lesion, wide bifurcation angle, and high risk of hemodynamic deterioration associated with potential SB occlusion) may require two-stent techniques. A more detailed evaluation of the anatomic severity and hemodynamic significance of intermediate LM lesions can be done by intracoronary imaging using intravascular ultrasound (IVUS) or optical coherence tomography (OCT), or physiologically using fractional flow reserve (FFR), to guide an appropriate PCI strategy and a PCI optimization in daily practice. The criteria for LM intervention are the following: LM diameter stenosis ≥70% by CAG, minimum lumen area (MLA) ≤6.0mm^2 by IVUS or OCT, and fractional flow reserve (FFR) ≤0.80.[9]

INTRAVASCULAR ULTRASOUND AND OPTICAL COHERENCE TOMOGRAPHY GUIDANCE

Intravascular ultrasound examination is of paramount importance in the determination of the vessel size, lumen area, and plaque size and distribution within the LM and its branches, the LAD and LCX arteries.[15] The IVUS-derived MLA can provide anatomic information on the ischemic burden of the LM lesion. An MLA of 6.0mm^2 on IVUS is a safe cut-off value for deferring intervention of intermediate LM disease.[37] An MLA of 4.5mm^2 could be a potential cut-off value for deferring an intervention in Asian patients.[38] The pre-procedure "spiky" carina or "eyebrow" sign at the origin of the side branch in IVUS or OCT predicts carina shift and restenosis after LM bifurcation PCI in a single-stent strategy.[38] Ideally, pullbacks from both the LAD and LCX should be obtained to aid complete information on LM bifurcation and avoid overestimation of the MLA within the LCX ostium by the noncoaxial orientation of the catheter from a LAD pullback.[37] Intravascular ultrasound ensures stent optimization by identifying stent under-expansion or malapposition, edge dissection, or significant residual disease, which could not be detected on CAG. Intravascular ultrasound optimization corrects stent under-expansion which ensures improved clinical outcomes after LM bifurcation PCI requiring two stents. Stent under-expansion is the most important cause of DES failure. A minimal stent area (MSA) less than 5.0 to 5.5mm^2 is the best predictor of DES in-stent-restenosis (ISR) and early stent thrombosis.[39,40] Kang et al. reported that the MSA cut-off values used to prognosticate ISR on a segmental basis were 5.0mm^2 for ostial LCX, 6.3mm^2 for ostial LAD, 7.2mm^2 for a polygon of confluence, and 8.2mm^2 for proximal LM in IVUS analysis (the so called 5-6-7-8 rule of criteria).[41] Stent under-expansion in LCX ostium and remaining metallic carina after two-stent techniques in LM is liable to engender restenosis, and IVUS-guided stent expansion is consequently useful.

The ongoing RCTs – Optimal (NCT04111770), Infinite (NCT04072003), and DK Crush VIII (NCT03770650) – aim to provide definitive evidence on the clinical impact of IVUS-guidance during PCI to an unprotected LMCA.

OCT offers a more detailed assessment of the lumen and intima compared to IVUS because of its higher resolution. The limitations of OCT include its difficulty in clearing the LM lumen with adequate flush and reduced depth of penetration compared with IVUS. Power injection of 20mL of contrast over 5 seconds and a pressure of 500 psi can improve the image quality. The limited depth and the need of blood clearance pose a significant challenge for OCT-guided LM bifurcation PCI due to the inclusion of more artifacts. 3D-OCT provides significantly less incomplete strut apposition than 2D-OCT guidance, after LM bifurcation stenting, followed by kissing balloon inflation (KBI) with the assessment of the guidewire recrossing point.[42] Another advantage of OCT guidance is a clear visualization of the calcium border and an adequate lesion preparation using an atherectomy in calcified lesions.

FRACTIONAL FLOW RESERVE ASSESSMENT

Approximately 30 to 40% of intermediate LM lesions demonstrate a visual-functional mismatch in the physiologic assessment done by FFR[43,44] and the LM lesions with FFR values of >0.75 or 0.80 could be safely deferred.[43,45] LM bifurcation lesions involving the bifurcation of the LAD and LCX can be assessed with two FFR measurements, one in the LAD and another with the pressure wire in the LCX. However, interpreting the LM FFR in the presence of significant downstream branch lesions, such as LAD stenosis, is more perplexing because the LM and LAD lesions act like serial lesions, and the true flow across the LM is potentially reduced by severe downstream lesions, artifactually increasing the LM FFR. This requires a PCI of the downstream lesions to obtain the true LM FFR.[6] The need for PCI of the ostial LCX after LM-LAD crossover stenting may be reduced by FFR guidance.[46] Either the CAG or FFR-guided technique may be recommended for provisional SB stenting, given the identical 1-year MACE rates with both approaches in the DK Crush VI trial.[47] However, further RCTs are needed to validate the efficacy of this strategy.

CRAFTING A STENTING STRATEGY

After the heart team discussion, the decision is made to proceed with PCI of LM bifurcation if it could be performed by experienced operators at a catheterization laboratory equipped with intracoronary imaging, invasive coronary physiology, and mechanical circulatory support.[48]

A straightforward two-stent strategy has been usually considered to be inferior to a provisional stenting, due mainly to the higher rates of periprocedural myocardial infarction (MI), repeat revascularization, and stent thrombosis with multiple stents. The Definition (Definitions and Impact of Complex Bifurcation Lesions on Clinical Outcomes After Percutaneous Coronary Intervention Using Drug-Eluting Stents study) II trial has potentially overcome such existing concerns and has demonstrated that the two-stent technique is associated with improved clinical outcomes compared to the one-stent strategy in complex LM bifurcation lesions.[49] Until recently, two RCTs were comparing the provisional stenting strategy and the complex two-stent technique for true distal LMCA bifurcation lesions, and the key findings are summarized in table 1. The DK Crush V trial demonstrated that LM bifurcation PCI using a planned DK crush 2-stent strategy resulted in lower rates of target lesion failure (TLF), target vessel MI, or clinically driven TLR at 1 year than the provisional stenting strategy.[50] In contrast, the EBC-Main (European Bifurcation Club Left Main Study) demonstrated that the provisional approach was associated with numerically (but not significantly) fewer MACEs (a composite of death, MI, and TLR) than a planned dual stenting.[51] Based on this result, the emphasis is to adopt a stepwise, layered provisional approach star-

Table 1. Recent randomized controlled trials of left main bifurcation stenting

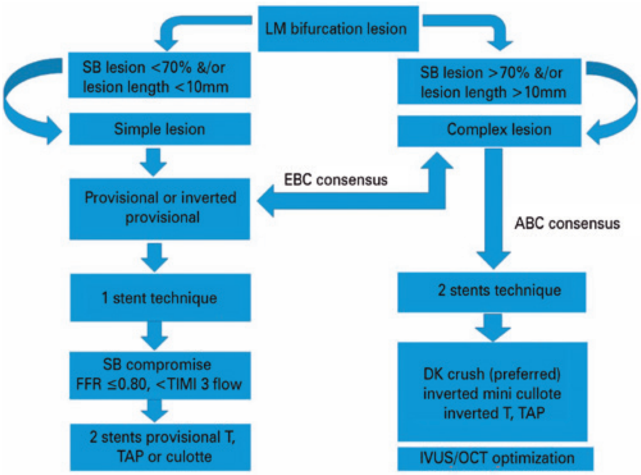
	EBC-Main trial	DK Crush V Trial
Design	Provisional strategy versus straightforward 2-stent strategy	Provisional strategy versus DK crush
Number of patients	467	482
Mean age, years	71.1	64.5
Male sex, %	76.9	80.2
Diabetes, %	27.4	27.2
Operator experience	≈150 PCI/y	≈300 PCI/y and ≈20 left main PCI
Mean SYNTAX score	22.9	30.6
Bifurcation angle	81.3_	78
Length of side branch lesion,mm	6.9	16.4
Complex bifurcation, %	Not classified	31.5
Use of IVUS guidance	Not mandated, 32.5%	Not mandated, 41.7%
Straightforward 2-stent strategy	Culotte (53%), T/TAP (33%), DK crush (5%)	DK crush
Conversion rate to 2-stent in provisional strategy, %	22	47
Primary endpoint	Death, MI, or TLR	TLF, defined as a composite of cardiac death, target vessel MI, or TLR
Key findings (provisional versus 2-stent)	1 y: 14.7% versus 17.7%; P=0.34	1 y: 10.7% versus 5.0%; p=0.02 3 y: 16.9% versus 8.3%; p=0.006

Source: the authors.
DK: double kissing; PCI: percutaneous coronary intervention; IVUS: intravascular ultrasound; TAP: T and protrusion; MI: myocardial infarction; TLR: target lesion revascularization; TLF: target lesion failure.

ting with a single stent and not "prejudge" the situation by deciding on a more complex two-stent strategy from the outset. However, further larger RCTs are needed to validate this. This study was not designed to compare one-stent versus two-stents strategies. This was a superiority trial that revealed neutral results of a provisional approach that required a second stent in at least one-fifth of the cases versus a straightforward two-stent strategy comparing the culotte and T/T and protrusion (TAP) techniques in over two-thirds of the patients.

The vessel and lesion characteristics (plaque distribution, the diameter of the daughter branches, the angle between them and anatomy of the SB) dictate the treatment strategy. The provisional one-stent technique remains the default approach for LM bifurcation which is technically less demanding compared to complex two-stent stent techniques.[52] Crossover stenting followed by the proximal optimization technique (POT) is the recommended way for the provisional single-stent strategy in LM bifurcation allowing the deployment of a second stent in T, TAP, culotte fashion if required.[53] In current practice, a straightforward two-stent strategy may be required in complex LM bifurcation lesions (Figure 2). To stratify the most appropriate stenting strategy, the LM bifurcation is designated as simple or complex based on the Definition criteria.[49] It is considered simple if the SB diameter stenosis is <70% and the lesion length <10mm which is observed in 75% of cases. A complex LM bifurcation lesion has a SB diameter stenosis and a lesion length of >70% and >10mm respectively. A simple lesion may become complex with the presence of two of the following six minor criteria: moderate to severe calcification; multiple lesions; LAD-LCX bifurcation angle >70; MB reference vessel diameter <2.5mm; a thrombus-containing lesion; and MB lesion length >25mm. The two-stent strategy may be adopted according to the bifurcation anatomy and the operator's expertise.

Until recently, two dedicated RCTs comparing the DK crush technique with the culotte and provisional stenting for true LM bifurcation lesions demonstrated the superiority of the planned DK crush technique concerning the primary composite ischemic endpoint over 3 years of long-term follow-up.[21,54] In a recent network meta-analysis, including 5,711 patients treated using five different bifurcation PCI techniques (provisional, crush, culotte, T-stenting/T- stenting and protrusion, and DK crush), DK crush was associated with fewer MACEs compared with provisional stenting driven by lower TLR, whereas no benefit of the other two-stent techniques over provisional stenting was observed.[55] Although DK crush has emerged as a preferred strategy for true LM bifurcation lesions, it should be recognized that it is technically challenging and should be performed by experienced operators. This technique can be used in virtually all types of complex LM bifurcation efficaciously, albeit there is a lack of consensus, and few data, on the optimal two-stent technique strategy.[9] A final KBI with re-POT is mandatory to optimize stent expansion and preserve the bifurcation anatomy.[52,56]



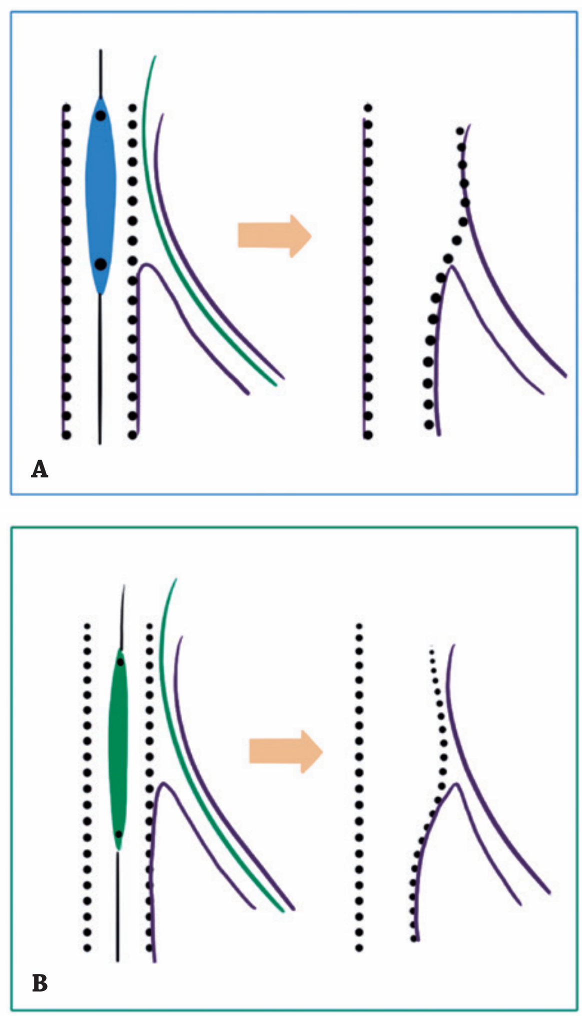
Source: Dash D, Chen SL, Zhang JJ. Left main stenting: What we have learnt so far? Indian Heart J Interv. 2018;1:18-30. Figure 1: Algorithm for left main bifurcation percutaneous coronary intervention; p. 22.[16]

LM: left main; SB: side branch; FFR: fractional flow reserve; TIMI: Thrombolysis in Myocardial Infarction; TAP: T and protrusion; DK: double kissing; IVUS: intravascular ultrasound; OCT: optical coherence tomography.

Figure 2. Algorithm for left main bifurcation percutaneous coronary intervention.

PROVISIONAL ONE-STENT TECHNIQUE

The provisional stenting with one-stent crossover into the LAD or the MB is the default strategy in LM bifurcation lesions. Left main with insignificant (<50%) ostial LCX or SB lesion with a lesion length of <10mm, a non-left dominant coronary system, or LCX with <2mm diameter favours a one-stent approach. An inverted provisional approach (provisional one stent from LM to LCX) should be adopted if the predominant lesion is in the LCX (behaving as MB) without ostial disease of LAD. In the provisional technique, a stent is deployed from the LM to the LAD after sizing with distal MB reference. The stent should be implanted proximal enough to the SB to accommodate a short, greater-diameter balloon sized to the LM and at least 6 or 8mm in length. Proximal optimization technique is then performed at the caliber of the proximal MB up to the carina level with a balloon diameter sized 1:1 according to the proximal MB (Figure 3). This allows strut protrusion into the SB with a larger strut opening, and no or limited carina shifting for smooth guidewire exchange. The distal shoulder of the balloon is positioned accurately at the carina for better results. Albeit both semi-compliant and non-compliant balloons are viable options, the non-compliant balloon is favoured in the presence of stent under-expansion. Three options for the SB are reported: the crossover stenting is followed by POT with no SB dilatation or KBI; if the SB demands intervention, the guidewires are then exchanged; the LAD guidewire can be withdrawn and passed through the most distal cell (most proximate to carina) to the LCX, thus allowing the projection of struts in the ostial segment of the SB opposite the carina. The "jailed" guidewire in the LCX is withdrawn and advanced to the LAD. An alternative technique is to create a gentle double curve at the fresh wire tip, crossing the LM into the LAD with the tip pointing upward and then pulling back gently with the tip rotating downward to enter the LCX. Then POT, KBI, and re-POT are performed (Figures 4 to 8). Proximal optimization technique, SB inflation, and re-POT are performed without KBI (Figure 9)[57] which needs further clinical validation.



Source: the authors.

Figure 3. Illustration of balloon position in proximal optimization technique. (A) The correct position is the distal marker at the carina level. (B) A distal marker distal to the carina causes malapposition at the proximal segment and carina shift.

The short non-compliant balloons with minimal overlap[58] are utilized for KBI to avert dissection and prevent oval distortion in the LM. Balloon diameters are chosen according to Murray's law, and the balloon is inflated in the SB first, followed by simultaneous deflation. To minimize proximal deformation, a modified KBI approach has been proposed, utilizing asymmetric inflation pressures: the SB is first inflated to 12atm, then partly deflated back to 4atm with simultaneous inflation of the MB balloon at 12atm.[59] Routine KBI fails to demonstrate a clear benefit for a one-stent strategy, but it is compulsory for two-stent techniques, including provisional stenting converting into a two-stent technique. The COBIS (Korean Coronary Bifurcation Stenting) registry demonstrates a higher MACE rate with KBI.[60]

PROVISIONAL STENTING OF THE SIDE BRANCH (CONVERSION TO A TWO-STENT STRATEGY)

T stenting

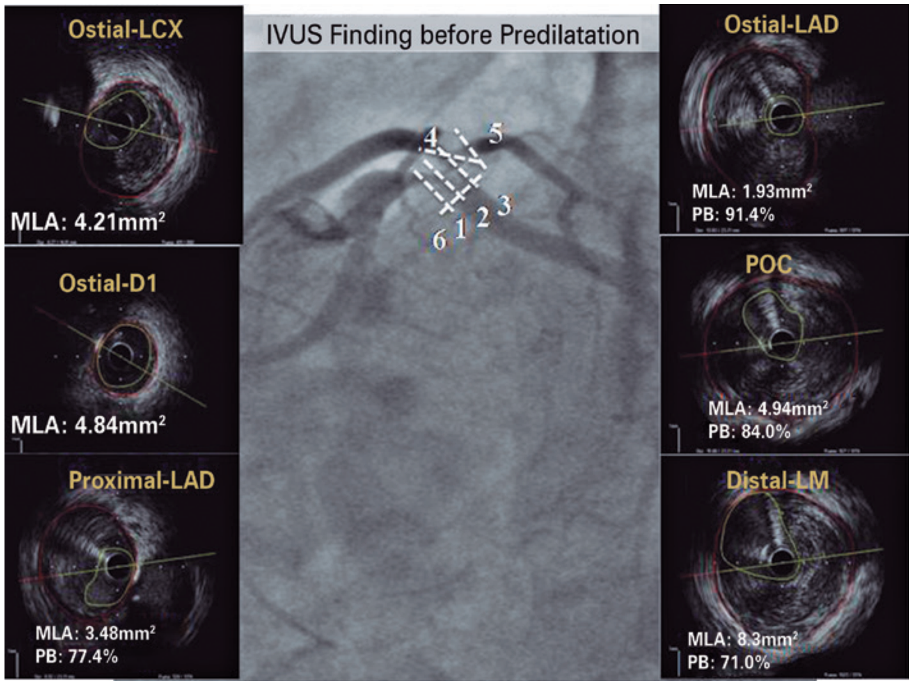
Initially, all the steps of the provisional technique including distal rewiring and KBI are performed. Then if the bifurcation angle is close to 90°, the second stent is deployed in a T fashion which permits stent strut coverage of the bifurcation without the need of floating or overlapping stent struts.[61] However, bench test data have documented that the bifurcation angle commonly is not 90° and this might result in incomplete SB ostium scaffolding or stent protrusion inside the proximal MB. A suboptimal SB ostium coverage may lead to restenosis whereas protruding struts may jeopardize access to the distal MB.

T AND PROTRUSION STENTING

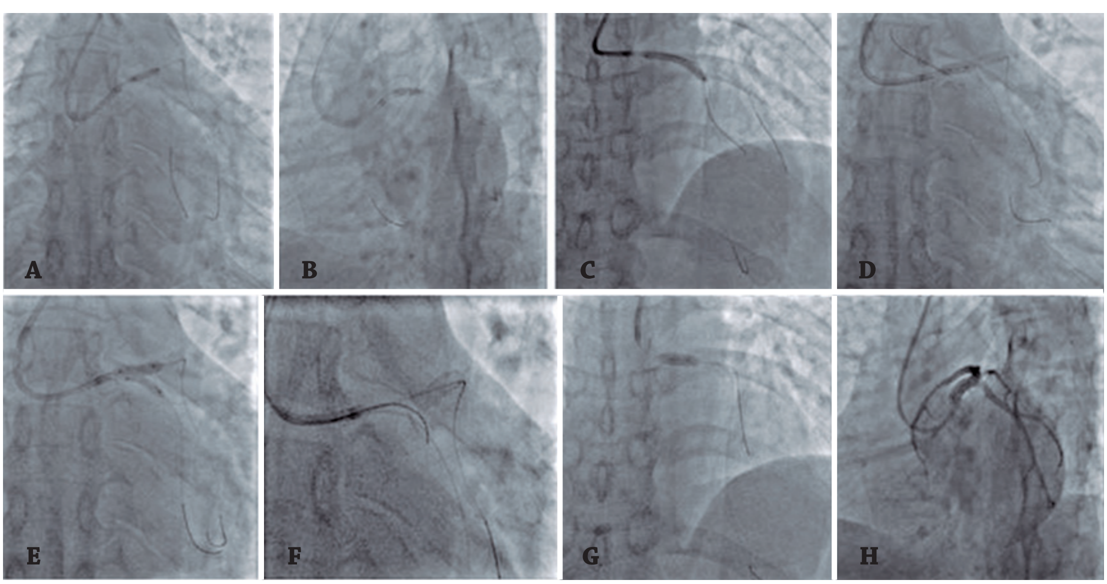
The recognition of the pitfalls of T stenting resulted in the development of the TAP technique.[62] A stent sized to the distal vessel is deployed from the LM to the LAD, and POT is performed. The jailed guidewire is withdrawn, and the LCX is recrossed through the distal cell closest to the carina. Then the LCX stent is deployed with minimal protrusion (1 to 2mm inside the LM stent) while maintaining an uninflated balloon in the LAD. After deployment of the LCX stent, the balloon of the stent is partially pulled back, and a high-pressure inflation is repeated to expand the stent optimally at the level of LCX ostium (the balloon inside the LAD is still kept uninflated during this phase). After alignment of the LAD balloon and the LCX stent's delivery balloon, KBI is performed by inflating simultaneously these two balloons (Figure 10). Some bench tests suggest a sequential high-pressure inflation with non-compliant balloons, but simultaneous inflation should follow, and the kissing balloon deflation should be simultaneous (to keep the neocarina in a central position). The TAP stenting eliminates the requirement for a second SB rewiring. A repeat final POT is considered when a long segment of the stent in the MB is present and long overlaps between the balloons during kissing have occurred (this can result in an oval MB result). An anticipated pitfall of this technique is the engendering of a single-layer neocarina length of which is determined by the takeoff angle of the SB and the site of strut crossing of the neocarina. With a T-shaped takeoff, a minute protrusion of the LCX stent inside the LM is required to cover the LCX ostium. In contrast, acute (Y-shaped) SB angles are associated with longer, oval-shaped SB ostia, warranting the need for wider protrusion of the stent.

Source: Dash D, Chen SL, Zhang JJ. Left main stenting: What we have learnt so far? Indian Heart J Interv. 2018;1:18-30. Figure 2: A and B: Baseline CAG showing simple "true" LM bifurcation lesion (Medina 1, 1, 1); p. 22.[16]

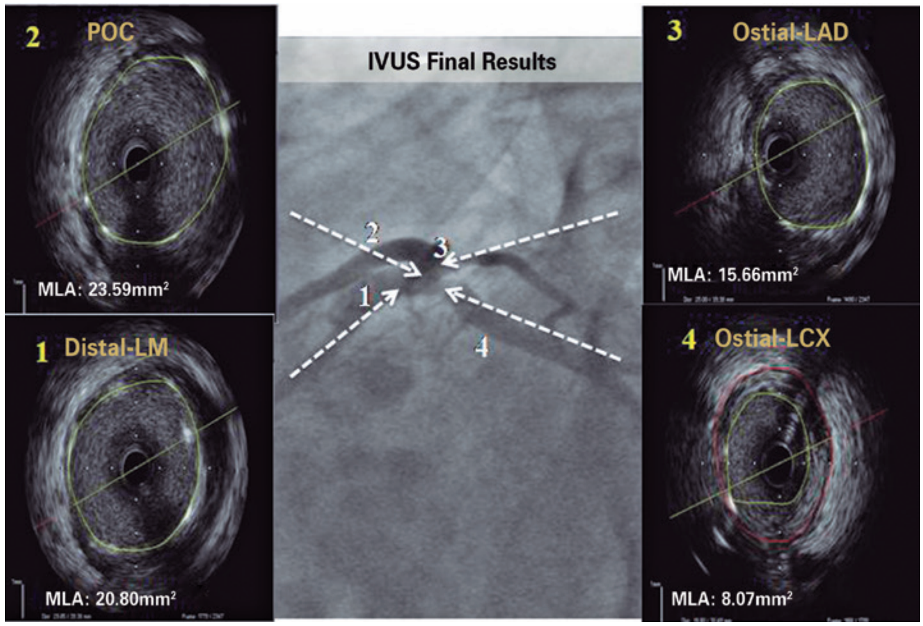
Figure 4. Baseline coronary angiography showing simple true left main bifurcation lesion (Medina 1,1,1).



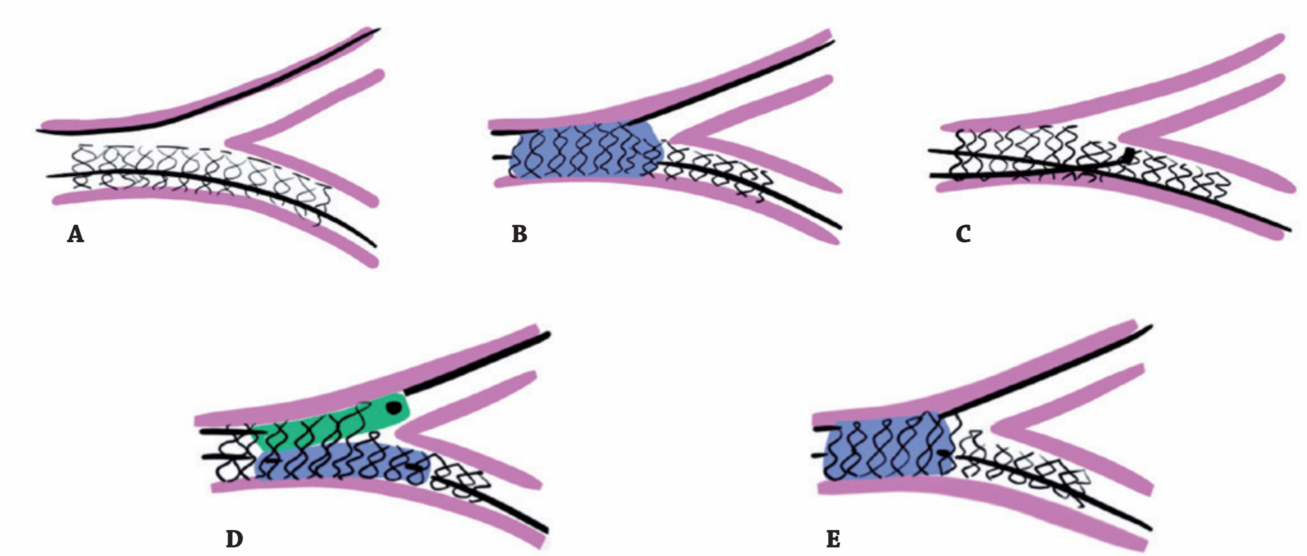
Source: Dash D, Chen SL, Zhang JJ. Left main stenting: What we have learnt so far? Indian Heart J Interv. 2018;1:18-30. Figure 3**:** IVUS pullback from LAD, first diagonal, and LCX; p. 23.[16]
IVUS: intravascular ultrasound; LCX: left circumflex artery; LAD: left anterior descending artery; MLA: minimum lumen area; PB: plaque burden; POC: poligon of confluence; LM: left main.
Figure 5. Intravascular ultrasound pullback from left anterior descending artery, first diagonal and left circumflex artery.



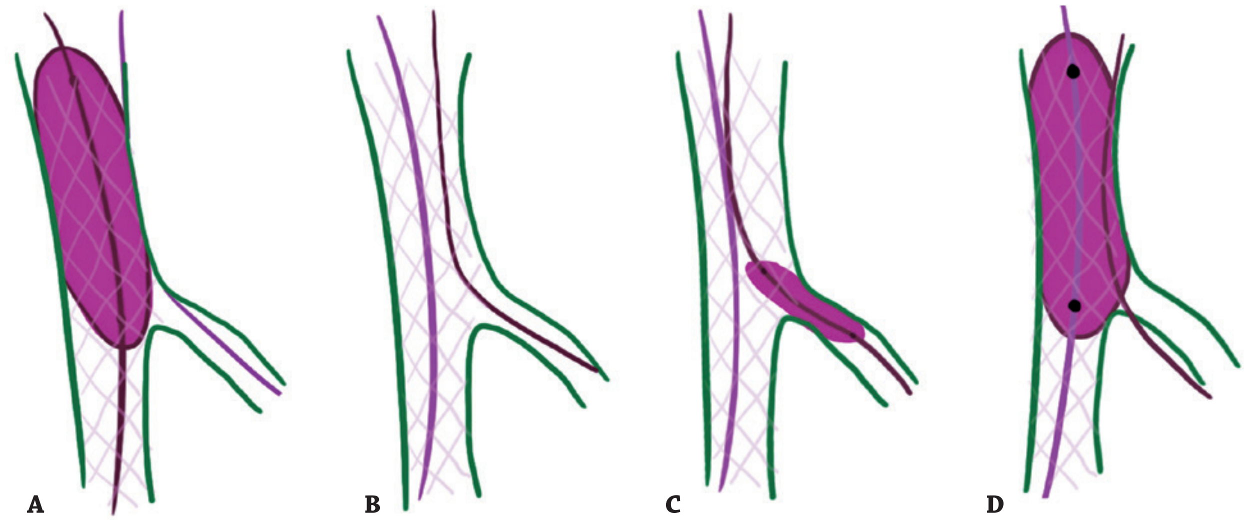
Source: Dash D, Chen SL, Zhang JJ. Left main stenting: What we have learnt so far? Indian Heart J Interv. 2018;1:18-30. Figure 4: Step-by-step illustration of provisional one-stent technique. (A) Predilatation of the LAD with a 3.5 x 10mm cutting balloon at 12 ATM. (B) Predilatation of the LCX with a 3.5 x 10mm cutting balloon at 12 atm. (C) Stenting of the LM-LAD with a 3.5 x 30mm DES at 10 ATM with a jailed guidewire. (D) LM proximal optimization technique (POT) using a 5 x 8mm non-compliant balloon at 20 ATM. (E) Recrossing of the LCX through the distal stent cell. (F) Final kissing balloon inflation (KBI) using a 4 x 12mm non-compliant balloon in the LAD and a 3.5 x 12mm balloon in the LCX at 8 ATM. (G) LM re-POT using a 5 x 8mm non-compliant balloon at 20 ATM. (H) Final result; p. 23.[16]
Figure 6. Step-by-step illustration of provisional one-stent technique. (A) Predilatation of left anterior descending artery lesion with a cutting balloon. (B) Predilatation of left circumflex artery lesion with a cutting balloon. (C) Stenting of the left main-left anterior descending artery with a jailed guidewire in the left circumflex artery. (D) Provisional optimization technique of the left main using a short, larger diameter balloon sized to the left main. (E) Final kissing balloon inflation using a non-compliant balloon in the left anterior descending artery and left circumflex artery at medium pressure. (F) Re-provisional optimization technique of the left main. (G) Result.



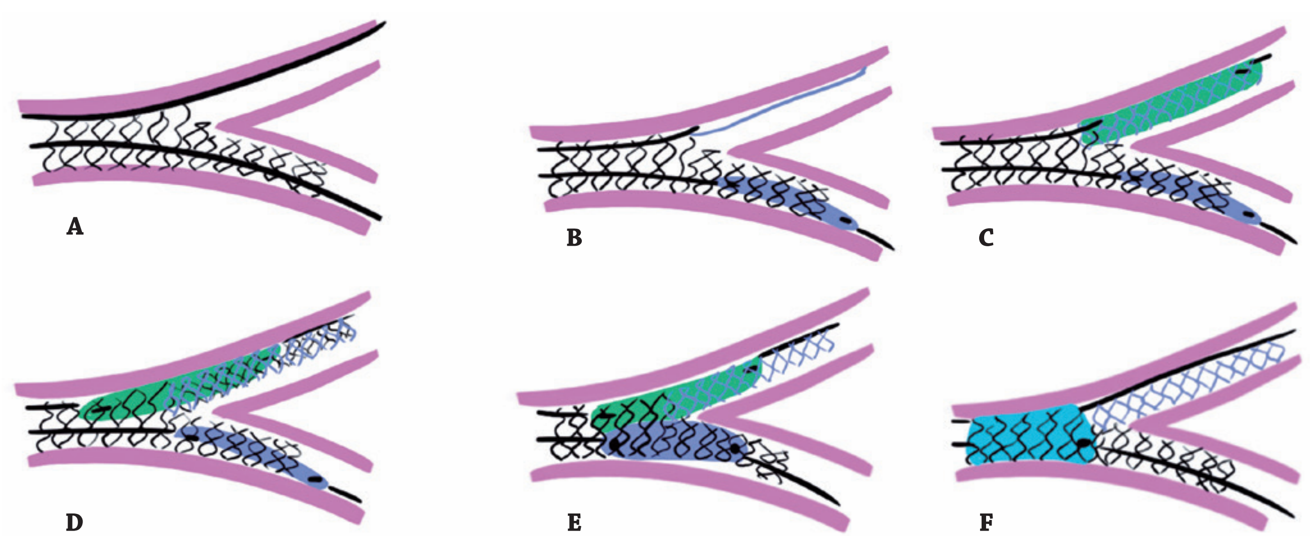
Source: Dash D, Chen SL, Zhang JJ. Left main stenting: What we have learnt so far? Indian Heart J Interv. 2018;1:18-30. Figure 5**:** IVUS depiction of the final result; p. 24.[16]
IVUS: intravascular ultrasound; POC: polygon of confluence; MLA: minimum lumen area; LAD: left anterior descending artery; LM: left main; LCX: left circumflex artery.
Figure 7. Intravascular ultrasound depiction of the result.



Source: adapted from Burzotta F, Lassen JF, Lefèvre T, Banning AP, Chatzizisis YS, Johnson TW, et al. Percutaneous coronary intervention for bifurcation coronary lesions: the 15th consensus document from the European Bifurcation Club. EuroIntervention. 2021;16(16):1307-17. https://doi.org/10.4244/EIJ-D-20-00169. Figure 2: Recommended steps for provisional technique; p. 5.[52]
Figure 8. Schematic illustration of provisional stenting with one stent crossover. (A) Stenting of the main branch (left main) to left anterior descending artery across the side branch (the left circumflex artery) take-off with the stent sized 1:1 according to the left anterior descending artery. (B) Proximal optimization technique with a short balloon with diameter adapted to the left main diameter with the tip marker ending in front of the carina. (C) Distal recrossing (closest to carina) of the side branch with the main branch guidewire or a new guidewire. The double bent guidewire tip shape easily allows entering the distal part of the side branch ostium. (D) Kissing balloon inflation with two short, preferably non-compliant balloons sized with both distal branches, with the side branch balloon minimally extending beyond the ostium. (E) Re-proximal optimization technique.



Source: the author.
Figure 9. Illustration depicting proximal optimization technique, side proximal optimization technique. (A) First proximal optimization technique. (B) Guidewire exchange. (C) Side branch dilatation. (D) Re-proximal optimization technique.



Source: adapted from Burzotta F, Lassen JF, Lefèvre T, Banning AP, Chatzizisis YS, Johnson TW, et al. Percutaneous coronary intervention for bifurcation coronary lesions: the 15th consensus document from the European Bifurcation Club. EuroIntervention. 2021;16(16):1307-17. https://doi.org/10.4244/EIJ-D-20-00169. Figure 4: Recommended steps for T stenting and minimal protrusion technique; p. 8.[52]
Figure 10. T stenting and minimal protrusion. (A) The provisional stenting up to the kissing balloon inflation. (B) The positioning of the side branch stent with minimal protrusion into the left main and an uninflated balloon in the distal main branch (left anterior descending artery). (C) Stenting of the side branch (left circumflex artery) with the main branch balloon uninflated. (D) Pulling back of the side branch balloon and high-pressure inflation of the side branch ostium. (E) Kissing balloon inflation after alignment of the main branch balloon and the side branch stent's balloon. (F) Proximal optimization technique.

INTENTIONAL TWO-STENT TECHNIQUES

Inverted culotte stenting

After adequate predilation of the LM to LAD and LCX, the first stent is implanted in the most angulated branch, normally the SB (LM-LCX) that protrudes inside the proximal MB (LM). The stent is sized according to the diameter of the LCX and long enough to permit POT in the LM. Post-dilation of the stent at the caliber of the LM up to the carina level is performed (POT technique). Distal rewiring LAD is performed proximate to the carina utilizing the pullback technique from the LCX. High pressure dilatation of LM-LAD (or KBI) is performed to open the struts towards the LAD. A second stent is advanced from the LM to the LAD through the struts of the first and is then deployed followed by second POT. The LCX stent is rewired through the distal cell followed by a final KBI utilizing short non-compliant balloons (sequential inflation at high pressure followed by simultaneous KBI). The procedure culminates with the final POT. In current culotte stenting, POT is recommended after the first- and second-stent deployment, as well as a final POT after KBI. It is advisable to prevent a long overlap of stents in the proximal MB, whenever feasible (mini-culotte). This technique ascertains near-perfect coverage of the carina and the LCX ostium. The main disadvantage of the technique is that rewiring both branches through the stent struts can be technically demanding and time-consuming. A bench study reports that a "napkin" or a gap normally remains at the SB ostium after the culotte stenting, leading to failure to completely scaffolding the ostium and resulting in increased ISR, TLR, and ST.[63] The culotte stenting technique can be improved by performing a 'double kissing strategy' called DK culotte by optimizing the SB result with an additional KBI before stenting the MB.[64] DK culotte allows a significant reduction in the total procedural time while resulting in a better optimized overall final strut apposition. In that regard, this technique may be superior not only to conventional culotte but also when compared to DK Crush. The clinical validity of this remains to be tested in a larger RCT.[6]

Double kissing crush stenting

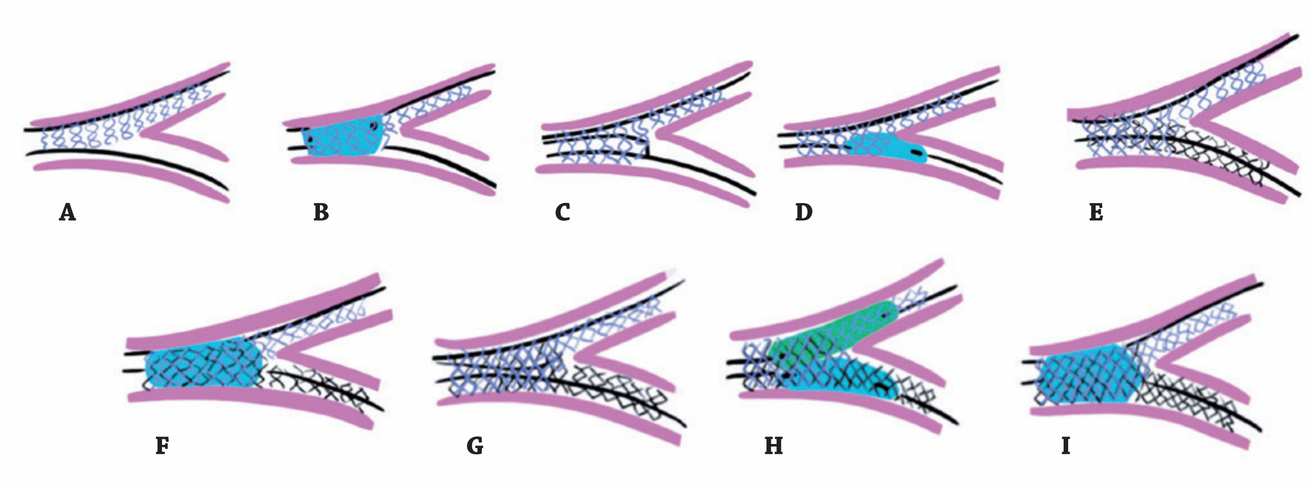
The crush technique was reported by Colombo in 2003.[65] Subsequently, a lack of predictability in wire/balloon recrossing was observed after deployment of the second stent. Regrettably, the final KBI performed immediately after the classic crush technique is difficult or sometimes non feasible, resulting in worse outcomes during the follow-up. An unsatisfactory and incomplete final KBI (20-25% after classic crush) is associated with high rates of ST and in-stent-restenosis (ISR). A bench test attributes this kissing failure to the stent platform, irregular and diminutive stent cell, rigorous distortion of the MB stent, and the anomalous overlapping of three layers of stent struts.[66] DK-crush technique (Table 2)[9] introduced by Chen et al employs the KBI twice to overcome the limitations of the classical crush technique.[67]

After predilatation of both the LAD and the LCX, a stent (adequate length to cover the LCX disease and sized 1:1 according to the LCX) is placed from the LM into the LCX. Two to 3mm of the LCX stent ought to protrude in the LM. A balloon (sized according to the MB) is placed in the LM-LAD. The LCX stent is deployed, and the balloon of the stent is marginally pulled back and inflated at high pressure (the balloon in the LM-LAD is still kept uninflated during this phase). This step called "SB optimization" is aimed at achieving the best stent apposition and expansion at the SB ostium.[68] Then the guidewire and the balloon from the LCX are removed. The prepositioned balloon in the LM-LAD is inflated to crush the protruding segment of the LCX stent against the LM wall. The LCX is rewired through the proximal cell of the stent, followed by the first KBI according to a sequential technique (alternating isolated high-pressure inflations of each followed by final simultaneous KBI and deflation). Following the removal of the balloons and the LCX guidewire, a stent is deployed in the LM-LAD segment, which is followed by POT. The wire is again recrossed into the LCX (through proximal to mid cell) and the final KBI according to a sequential technique (alternating isolated high-pressure inflation of each followed by final simultaneous KBI and deflation) is followed by re-POT. As a result, the DK crush technique consists of seven steps: SB stenting with 2 to 3mm protrusion into the MB, balloon-crush of the SB stent, first SB rewiring through the proximal stent cell, first KBI, MB stenting followed by POT, second rewiring of the SB through the proximal stent cell, final KBI, and POT (Figure 12).

Table 2. Comparison of the double kissing crush with the classical crush stenting technique.

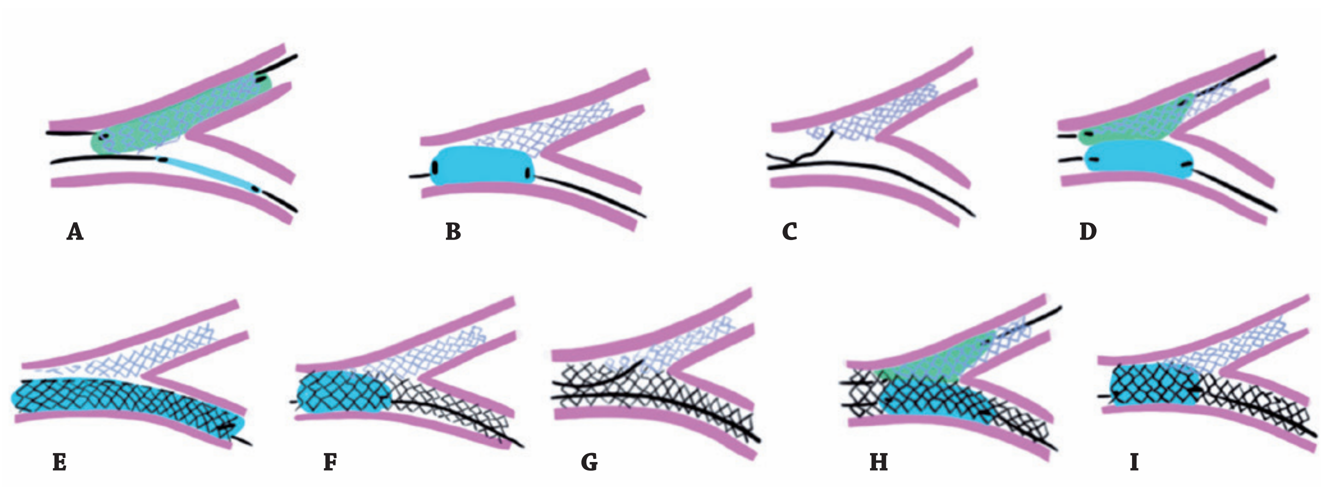
Variables	DK crush	Classical crush
Guide catheter	6F	7F
Anatomy	Suitable for all bifurcation angles	Unsuitable for wide angled bifurcation
Procedure type	Straightforward and reliable	Complex
Procedure time	Short	Longer than DK crush
Contrast use	Less	More
First kissing balloon inflation	Done	Not done
Final kissing balloon inflation	100%	70-80%
Kissing quality	Satisfactory	Unsatisfactory (abluminal side branch wiring)
Metal overlap	Less (two layers)	More (3 layers)
Side branch ostial scaffolding	Full	Incomplete
Stent thrombosis & in-stent restenosis	Negligible	Significant

Source: Dash D. Double kissing crush in left main coronary bifurcation lesions: A crushing blow to the rival stenting techniques! Indian Heart J. 2018;70(5):758-61. Table 1. p. 760.[9]



Source: adapted from Burzotta F, Lassen JF, Lefèvre T, Banning AP, Chatzizisis YS, Johnson TW, et al. Percutaneous coronary intervention for bifurcation coronary lesions: the 15th consensus document from the European Bifurcation Club. EuroIntervention. 2021;16(16):1307-17. https://doi.org/10.4244/EIJ-D-20-00169. Figure 6. Recommended steps for culotte technique; p.10.[52]

Figure 11. Inverted culotte technique. (A) Implantation of the stent from the left main into the side branch (left circumflex artery) sized 1:1 according to the side branch. A short left main coverage is preferred to limit the area with overlapping stents. (B) First proximal optimization technique. (C) Distal main branch rewiring according to the pullback technique. (D) Balloon dilatation of stent struts into the main branch. (E) Main branch stenting from the left main to the left anterior descending artery. (F) Second proximal optimization technique. (G) Distal side branch rewiring closest to carina. (H) Kissing balloon inflation. (I) Final proximal optimization technique.



Source: adapted from Burzotta F, Lassen JF, Lefèvre T, Banning AP, Chatzizisis YS, Johnson TW, et al. Percutaneous coronary intervention for bifurcation coronary lesions: the 15th consensus document from the European Bifurcation Club. EuroIntervention. 2021;16(16):1307-17. https://doi.org/10.4244/EIJ-D-20-00169. Figure 7: Recommended steps for double kissing crush technique; p. 11.[52]

Figure 12. Double kissing crush technique. (A) Side branch stenting with short main branch protrusion of 2 to 3mm. High pressure inflation after pulling back of the stent balloon. (B) Crushing of the protruding struts of the side branch by an appropriately sized balloon to proximal main branch after removal of side branch balloon and guidewire. (C) Proximal side branch rewiring. (D) High pressure dilatation of the side branch ostium followed by first kissing balloon inflation. (E) Main branch stenting across the side branch after removal of side branch guidewire. (F) First proximal optimization technique. (G) Second side branch guidewire recrossing through the proximal-mid stent cell. (H) Sequential balloon inflations to 16 atmospheres followed by second kissing balloon inflation to 12 atmospheres each, followed by simultaneous deflations. (I) Final proximal optimization technique.

CONCLUSION

Left main stenting is different from any other, with its bifurcation as a unique entity due to a larger myocardium at jeopardy, a wider bifurcation angle, and almost equal importance of the main branch and the side branch. According to the current evidence, percutaneous coronary intervention yields mortality and morbidity rates comparable with coronary-artery bypass surgery, updating the guideline for left main revascularization which prompts many interventional cardiologists to opt for percutaneous coronary intervention. However, despite the success of the treatment, left main bifurcation lesions continue to pose considerable technical challenges and require expertise and unique approaches for optimal results. Hence, an integrated approach combining more advanced devices with specialized techniques, adjunctive intracoronary imaging, physiologic guidance, and pharmacotherapy is critical to greatly improve percutaneous coronary intervention success rates and long-term clinical outcomes for this complex subset.

SOURCE OF FINANCING

None.

CONFLICTS OF INTEREST

The authors declare there are no conflicts of interest.

CONTRIBUTION OF AUTHORS

Conception and design of the study: DD, RM and NA; data collection: DD, RM and YPM; data interpretation: DD, NA,MK and BM; text writing: DD, RM and NA; approval of the final version to be published: DD, RM, NA, YPM, MK and BM.

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