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Technical Aspects of Revascularization during Primary Percutaneous Coronary Intervention

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Abstract:

Primary percutaneous coronary intervention (PCI) is the standard of care for patients presenting with ST-segment elevation myocardial infarction (STEMI). Successful revascularization not only depends on timely reperfusion but also on appropriate technical strategies during PCI. Complex lesion morphology, heavy thrombus burden, bifurcation involvement, and multivessel disease present significant challenges that may influence procedural success and long-term outcomes. Optimizing device selection, lesion preparation, and stent deployment techniques is essential to restore coronary flow and minimize complications such as no-reflow, side branch occlusion, or stent thrombosis.

Keywords: Primary PCI; Revascularization; STEMI; Thrombectomy; Bifurcation lesions; Multivessel disease; Stent optimization.

Introduction:

Primary percutaneous coronary intervention (PCI) is the preferred strategy for reperfusion in patients presenting with ST-segment elevation myocardial infarction (STEMI). It provides superior outcomes compared with fibrinolytic therapy by reducing infarct size, improving survival, and minimizing complications when performed in a timely manner **(1).**

Despite its proven benefits, the technical aspects of revascularization during primary PCI play a decisive role in procedural success. Factors such as heavy thrombus burden, multivessel disease, and bifurcation involvement significantly influence decision-making, requiring tailored strategies to restore optimal coronary flow **(2).**

Lesion preparation, device selection, and stent optimization are critical steps in primary PCI. Intravascular imaging modalities such as intravascular ultrasound (IVUS) and optical coherence tomography (OCT) help refine stent sizing, ensure adequate expansion, and prevent malapposition, thereby reducing the risk of restenosis and stent thrombosis **(3).**

Bifurcation lesions remain particularly challenging in the context of STEMI. While provisional stenting is often the preferred approach, complex bifurcation anatomy may necessitate advanced techniques to preserve side branch patency. Recent expert consensus highlights the importance of a stepwise strategy to balance procedural simplicity with clinical safety **(4)**.

Finally, the management of multivessel disease during primary PCI continues to be debated. Although culprit-only PCI remains the standard in most cases, selected patients may benefit from complete revascularization, as suggested by contemporary trials **(5).** Mastery of these technical considerations is essential for interventional cardiologists to maximize the short- and long-term benefits of primary PCI.

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Medina Classification:

Several classifications have been proposed to define the baseline characteristics of bifurcation lesions, but the most widely accepted is the Medina classification. This classification was first adopted in 2005 during the first congress held by the European Bifurcation Club in Bordeaux, France. Its success is based on its simplicity and the fact that it does not require memorization. Today, it remains the preferred reference, with new and interesting considerations added since its publication in 2006 (**6).**

Classification of coronary bifurcation lesions:

The objective is to associate each type of bifurcation with a prognosis, a technical difficulty or an optimal type of treatment, although this should not be regarded as systematically relevant. Many classifications have already been established in the field of interventional cardiology. It was therefore legitimate to classify the various types of significant lesion in the three segments of a bifurcation. Several classifications have been proposed, all of which require substantial memorization efforts (**7).**

The significant advantage of the classification established by Medina lies in its simplicity (Figure 1). Each segment is assigned a value 0 in the absence of significant stenosis and 1 in the presence of a stenosis >50%. A value of 0 or 1 is therefore assigned to each of the three segments separated in the following order: proximal segment (PM), main distal segment (DM), side branch (SB), the values being separated by commas (Figure 2) (**8**).

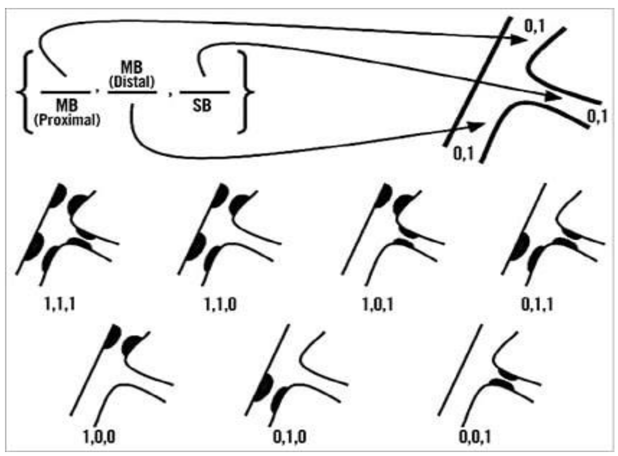

Figure (1): Medina's classification **(9).**

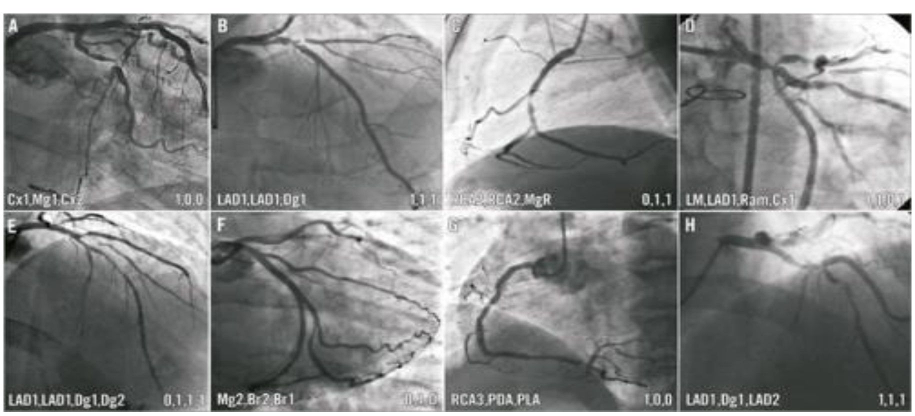

Figure (2): Eight examples of Medina's inspired denominations of a bifurcation lesion (LAD 1=proximal LAD, proximal to first septal branch). Coronary segments corresponding to bifurcation (trifurcation) are presented as in the

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Medina classification, PM, DM and SB separated by commas. Usual abbreviations (or segment numbers) and coronary segmentation are used. The choice of the order of segments is left to the operator, before the procedure, based on their importance (diameter, distal length, flow, myocardial mass, viability, etc.) but not on technical aspects **(9).**

The EBC suggested that the Medina classification should be accompanied by a clear pre-treatment definition of the SB and the distal MB. Indeed, it seems natural that the longest and largest distal branch should be designated as the main distal branch, given the linear relationship between diameter, length, flow and supplied myocardial mass. The definition of the three bifurcation segments should be established in the same manner as the Medina classification (with the two commas) **(9).**

The Medina classification was unanimously acclaimed and adopted during the first meeting of the European Bifurcation Club in September 2005 in Bordeaux. Although it has supplanted the previous classifications, it is still the subject of harsh criticism, especially in the USA (**10).**

Movahed maintains that a bifurcation lesion classification should be simple in order to be adopted and should include three major parameters **(9).**

– Is the diameter of the proximal healthy segment at least 2/3 of the sum of the diameters of both branches (otherwise the simultaneous kissing stent or SKS technique cannot be applied)?

– Are both ostia of a bifurcation involved or only the main or side branch? (When both ostia are involved the implementation of a complex strategy is inevitable).

– What is the angle between the branches (shallow or steep angle)?

The classification proposed by Movahed is impossible to memorise (Figure 3). It does not take into account the fact that the post-treatment diameter of the bifurcation proximal segment is equal to 2/3 of the sum of the distal diameters, according to Murray's law, modified by **Huo and Kassab (11**) and simplified by **Finet et al. (12).**

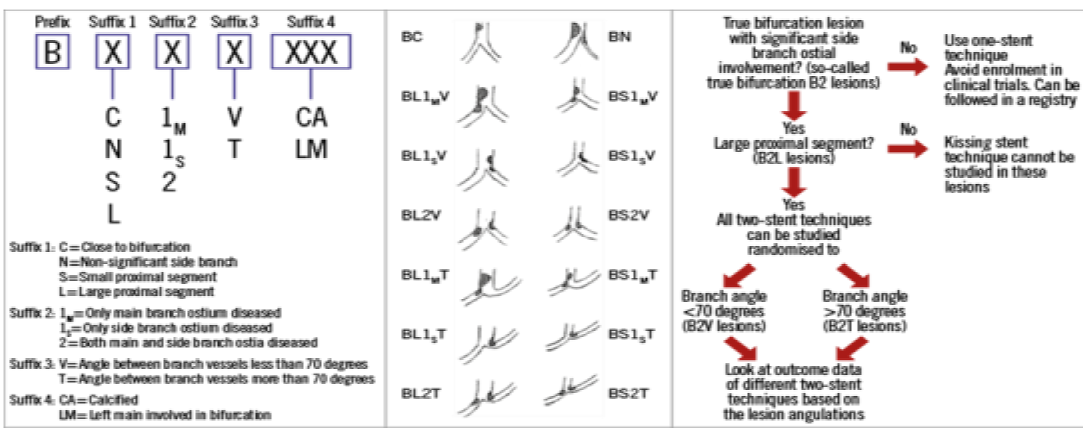

Figure (3): Movahed coronary bifurcation lesion classification (modified from Movahed references). Left panel: method to build a bifurcation class. Middle panel: simplified classification as the suffix 4 is not used. Right panel: Movahed recommendations for treatment and study design **(9).**

This classification is treatment-oriented, arbitrary and is not supported by any reliable clinical trial. The SKS technique has never been evaluated in any randomised trial or multicentre registry. The contraindication to the crush and culotte strategies in instances where the angle between the two distal branches (EBC: angle B for "between") is greater than 70° is based on two studies which are now relatively outdated (**13).**

Since then, it has been shown that technical failure in this setting is not exclusively related to the angle. In addition, the involvement of the ostia of the distal branches is difficult to define, given that a lesion in the SB ostium may be located in the wall of the MB and the degree of stenosis is overestimated both by visual assessment and by quantitative angiography not dedicated to bifurcations **(14).**

Regarding the only published patient-level meta-analysis combining data from the Nordic I and BBC One trials, Movahed suggested that the difference in the incidence of the combined endpoint (all-cause mortality, myocardial infarction and target vessel revascularisation) in favour of the provisional strategy was related to the greater lesion severity in the complex group (larger SB with longer and tighter lesions). Both study groups were adjusted by means of a propensity score, which resulted in the hazard ratio being higher in the simple strategy group than before adjustment. This study confirmed the superiority of the simple strategy in all subgroups (true bifurcation lesions, large SB, tight and long SB lesions, equivalent diameters of two branches, etc.) (**15).**

In September 2014, data were reported showing that overall mortality at five years was higher in the complex group (Behan, oral communication at the EBC 2014). The only available randomised study in favour of the complex strategy was weakened by the definition of a combined endpoint at 12 months after systematic coronary angiography at eight months (**16).**

Medina wrote that the main purpose of a bifurcation classification is that it "allows for homogenous terminology when comparing different series and techniques". A further issue relates to whether a bifurcation classification can predict outcomes or determine the interventional approach, in which case the classification could be modified (**17).**

The complexity of treating bifurcations arises mainly from the fact that bifurcations vary not only in anatomy (plaque burden, location of plaque, angle between branches, diameter of branches, bifurcation site) but also in the dynamic changes that occur during the procedure, such as plaque shift and dissection (**18).**

Medina's classification can be carried out by visual angiographic analysis. However, the fact that 2D angiographic analysis is not adequate for SB assessment should prompt the use of dedicated quantitative coronary angiography (QCA) software providing the three reference diameters, as well as lesion length, percentage and bifurcation angles (**19).**

Medina's classification can also be performed on the basis of data from IVUS, optical coherence tomography (OCT) or multislice computed tomography (MSCT). A Medina "fractional flow reserve (FFR) index" has also been considered, though this is not feasible as FFR can only be used to analyse two vessels and not three segments (**20).**

Rescue a Failed Provisional Approach:

The worst scenario in the setting of a bifurcation intervention with provisional technique is represented by complete loss of a relevant SB after MV stenting, with failure to rewire it. When SB occlusion is clinically relevant and any attempt to rewire it fails, operators should consider the possibility of a 'rescue' technique based on the advancement of a small balloon over the jailed wire with the aim of reaching the SB under the stent struts. Gentle balloon dilation may restore SB flow thus facilitating rewiring. In such circumstances, jailed balloon-induced MV stent distortion should be corrected by the POT and final kissing balloon inflation **(21).**

Different Stenting Techniques:

1. Provisional Stenting Compared to a Planned Two-stent Approach:

The provisional stenting strategy involves first stenting the main branch and then treating the side branch via stenting or balloon dilation, if necessary. Stenting of the side branch in provisional stenting can be implemented using T-stenting, T and small protrusion (TAP) stenting, culotte, or the reverse/internal mini-crush technique, as shown in Table 1. This varies from a planned two-stent approach, which requires the systematic use of 2-stents in a complex and coordinated fashion (**22).**

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The simple provisional stenting strategy is frequently associated with reduced procedure and fluoroscopy times, resulting in lower rates of procedure-related biomarker elevation compared to its two-stent counterpart techniques, which lend themselves to being considered the gold standard for CBLs. Despite the reduction in costs for patients with provisional stenting strategies, it becomes necessary to evaluate the effectiveness of the techniques to ensure that the quality of care is not compromised. For this reason, various randomized controlled trials and meta-analyses have been performed over several years to answer this question **(23).**

Table (1): Summary of provisional stenting strategy techniques **(22)**

Stenting Technique	**Provisional Single Stenting**	**T-stenting**	**TAP Stenting**
Summary of stenting strategy procedure	Placement of two wires (MB and SB) Pre-dilation of MB or both branches, when needed Stenting of the MB Stent optimization with proximal optimization technique (POT) Recrossing with a wire into the SB Performance of FKBI (Final kissing balloon inflation) with moderate pressure (8 atm) in the SB, until the balloon is fully expanded Final POT, if result in the SB is adequate after FKBI Placement of a second stent in SB when result is unsatisfactory.	Advance second stent into the SB (following dilation of the MB stent struts) Position stent at ostium of SB minimizing any possible gap. Perform second kissing balloon inflation.	A second stent is advanced into the SB to minimally protrude (1-2mm) into the MB A balloon is advanced into the MB The SB stent is deployed at (12+ atm), MB balloon is simultaneously inflated at 12+ atm. Both balloons are deflated and removed.
Stenting Technique (continued)	Culotte Stenting	Reverse/internal mini-crush stenting	
Summary of stenting strategy procedure (continued)	After MB stenting, second stent is advanced into SB protruding into the MB to overlap with proximal part of the MB stent and expanded following removal of MB wire. MB is rewired through the stent struts and dilated. Kissing balloon inflation is performed.	After stenting the MB, a second stent is advanced into the SB, and left in position without deployment. A balloon sized to the diameter of the MB, but shorter than the already-deployed stent, is advanced in the MB, positioned at the level of the bifurcation. SB stent is withdrawn approx. ≤ 3 mm into MB and deployed.	

		Deploying balloon is removed, and angiography is performed to verify the absence of distal dissection and need of additional stent. SB struts are recrossed with wire and balloon, sized to SB reference diameter and inflated at high pressure (12-20 atm). FBKI is performed.

Bail-Out Stenting for Failed Provisional Approach:

If the operators decide to use the provisional approach, there is almost always the possibility of placing a second stent , the result is not optimal or adequate. The available stent bail-out techniques are restricted to either T-stenting or culotte. In the case of T-stenting, there is an inherent risk of protrusion into the MB or gap at the side branch ostium. However, the T-stenting technique might provide better outcomes in LM than in non-LM bifurcations, since the LM angle is wide (nearly 90 degrees in a lot of cases), with less chance of leaving a gap than when the bifurcation angle is very narrow. The culotte technique also has the disadvantage of a double layer of stent struts in the proximal MB **(24).**

Bail-out strategies for a failed provisional approach include T, TAP, and culotte. Prior to proceeding with a second stent, the following steps should be considered **(25):**

1. Give intracoronary nitroglycerin.
2. Ensure adequate POT was performed.
3. While leaving the jailed wire in place, rewire the SB through a distal strut and then pull the jailed wire.
4. Perform KBI with NC balloons sized 1:1 with distal MV and 1:1 with SB.
5. Reperform POT on the proximal MV.
6. Consider the use of an alternative to KBI, which is POT-side-POT: Perform POT in the MV; dilate the SB ostium; and reperform POT on the MV.
7. If the SB is still compromised, then proceed with a two-stent technique.

Morbidity and Mortality:

The need for a repeat procedure after revascularization of the left main coronary artery (LM) may be associated with substantial morbidity and mortality given the large amount of subtended myocardium at risk **(26).**

Morbidity:

- **Acute Complications:** Include dissection, perforation, stent thrombosis, and side branch occlusion. These can lead to myocardial infarction, acute renal failure, emergency coronary artery bypass grafting (CABG), or death **(26).**
- **Long-Term Morbidity:** Restenosis, stent thrombosis, and progression of coronary artery disease can occur, necessitating repeat revascularization.

Mortality:

- **Short-Term Mortality:** Mortality rates in STEMI patients undergoing PCI have improved due to better techniques, but the risk remains higher in those with complex bifurcation lesions or complications during the procedure.

- **Long-Term Mortality:** Long-term survival is influenced by the success of the PCI, the presence of comorbidities, and the patient's adherence to secondary prevention strategies (e.g., antiplatelet therapy, lifestyle changes) **(26).**

TWO-STENT APPROACHES:

There are various two-stent techniques with different levels of complexity and indications, including the T-stent, TAP, culotte, mini crush, and DK crush techniques, as described herein.

T-Stent Technique:

The T-stent technique is favored for its simplicity but is reserved for bifurcation lesions with angles close to 90°. Provisional T stenting is used as a bailout method when the SB is deemed unsatisfactory after MV stenting. Following KBI during provisional stenting as described previously, both balloons are removed, and a stent is advanced down the SB wire and positioned at the SB ostium, ensuring that it does not protrude into the MV. The stent is deployed at nominal pressure, and then KBI is performed. Although this technique is simple and less laborious than crush techniques, the primary disadvantage is inadequate coverage of the ostium of the SB, leaving a gap between the stent implanted in the MB and the stent in the SB, which increases the risk for ostial restenosis at the SB **(27).**

TAP Technique

The TAP technique evolved to ensure complete stent coverage at the SB ostium. This technique is versatile and can be used in bifurcation lesions with more acute angles (70°-90°). Provisional TAP is a bailout method when the SB is deemed unsatisfactory after MV stenting. Following KBI as previously described in provisional stenting, both balloons are removed, and a stent is advanced down the SB wire and positioned just across the ostium of the SB with 1- to 2-mm stent protrusion into the MV.

The stent is deployed at nominal pressure, and KBI is performed. Although this technique ensures complete stent coverage at the SB ostium, the primary disadvantage is the formation of a neocarina at the bifurcation, which increases the risk for in-stent restenosis and stent thrombosis. Simultaneous inflation and deflation of the balloons is especially critical to avoid carinal shift **(23).**

Classic Crush and Mini Crush Techniques:

The crush techniques for stenting bifurcation lesions have evolved since its introduction in 2003 by **Colombo et al, (28)** with multiple variations in the technique having been described thereafter, including DK crush, mini crush, and nano crush. Significant ISR has been observed in about one-quarter of patients receiving bifurcation stenting, mostly due to SB stenting challenges, leading the investigators to develop the crushing technique to minimize the incomplete coverage of SB ostium. In the classic crush technique, both the MB and SB are wired and predilated. The first stent is advanced into the SB but left undeployed, and then the second stent is passed into the MB. The SB stent is retracted so that the proximal marker is seen protruding 4 to 5 mm from the carina into the main proximal vessel to ensure complete coverage of the SB ostium. The SB stent is then deployed, and the stent balloon is removed followed by the SB wire. Afterward, the MB stent is deployed, crushing the SB stent against the wall, leaving three layers of stents in the proximal portion of the MV and the SB ostium **(29).**

The classic crush technique provides a simple approach that enables complete coverage of the SB ostium and avoids the challenging delivery of an SB stent through the MB stent. However, some disadvantages have been reported, including the difficulty of using 6-F guide catheters to accommodate delivering two stents simultaneously. Another disadvantage is missing the final KBI as a standard part of the procedure, which would require wiring the SB through the MB stent. ISR was noted in 37.9% of the patients without KBI compared to 11.1% with KBI (**30).**

Three years after the introduction of classic crush technique, a modified version was proposed by **Galassi et al. (31**) called mini crush. In this technique, the two major differences from the classic crush technique were minimal protrusion of the SB stent into the MV, extending only 1 to 2 mm instead of 4 to 5 mm, and jailing the SB wire. They proposed positioning the SB stent about 1 to 2 mm into the MB, deploying the SB stent, and then crushing that stent using a balloon in the MB while jailing the SB wire. Afterward, an MB stent is delivered and then deployed, followed by rewiring the SB and removing the jailed wire, followed by final KBI. In that study by **Galassi et al. (31**) the restenosis rate was only 2% in the SB and 12.2% in the MB. One of the major advantages with minimal protrusion of the SB stenting is reducing the distortion of SB stenting and minimizing the number of stent layers at the SB ostium, facilitating the rewiring of the SB again while keeping a jailed SB wire to maintain an access to the SB.

DK Crush Technique

The challenges seen with the SB rewiring in the classic crush technique have led to the development of a modified approach to increase the success of SB rewiring for KBI and subsequently correct for any SB stent distortion.

The DK crush technique was first described by **Chen et al (32**) and **Jim et al. (33**) In this technique, after wiring both the SB and MB, a stent is delivered to the SB and positioned about 3 to 5 mm into the MV while a balloon is delivered to the MB. The stent in the SB is deployed, then the SB stent balloon and wire are removed first, and then the MB balloon is inflated to crush the SB stent. After crushing the SB stent, a wire is delivered into the SB and the first KBI is performed, and then the wire and the balloon from the SB are withdrawn. Next, the stent is delivered to the MB and deployed across the bifurcation. The second SB rewiring is performed and then another KBI. Eventually, another variation was recommended by applying POT to the MB stent before and after KBI to optimize stent geometry and facilitate wiring of the SB through the stent struts. The DK crush technique is characterized by higher rates of success of SB wiring compared to classic crush techniques and subsequently lower rates of SB stent restenosis or thrombosis. On the other hand, the major drawback of the DK crush technique is the need to rewire the SB twice (**34).**

Culotte Technique:

Culotte stenting is one of the modified techniques for two-stent bifurcations, especially when the angle between the MB and SB is < 70° and there is no significant size mismatch between the MB and the SB. Compared to crush techniques, stent distortion and the risk of missing parts of the lesion is minimized by the culotte technique. One downside associated with this technique is the need for two layers of stent in the proximal segment of the MB, which increases the risk of ISR (**35).**

The technique starts with wiring both the SB and the MB, then predilation of the SB is performed first, followed by delivering a stent to the SB and positioning the stent about 5 mm back into the MB. After deploying the SB stent, poststenting balloon dilation is performed, and the wire from the MB is removed. The MB is rewired again through the struts of the SB stent, followed by serial balloon dilations of the MB to open the SB stent struts more; the MB stent is delivered while maintaining the overlap between the two stents in the proximal MB. Prior to deploying the MB stent, it is important to remove the SB wire to avoid jailing a wire between two stents. After removing the stent balloon from the MB, POT is performed, followed by rewiring of the SB through the distal stent strut, KBI, and then final POT to ensure more optimization of the proximal segments where the two stents overlap (**36).**

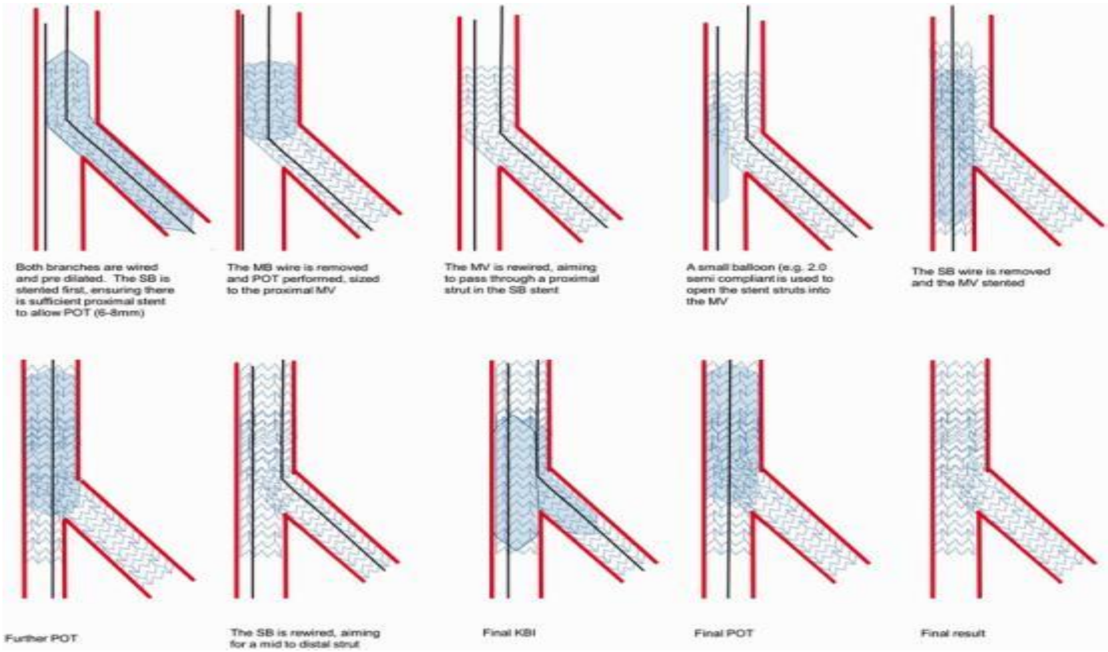

Figure (4): The culotte technique. This is most suited to lesions where the SB and the distal MW are of similar caliber. The SB is stented first, followed by a POT and rewiring of the MV, aiming for a proximal cross of the stent struts. The stent struts are opened with a low profile balloon and the MV stented. A further POT is performed before rewiring of the SB to minimize the risk of abluminal wiring. KBI inflation is performed, sized to the distal vessels **(37).**

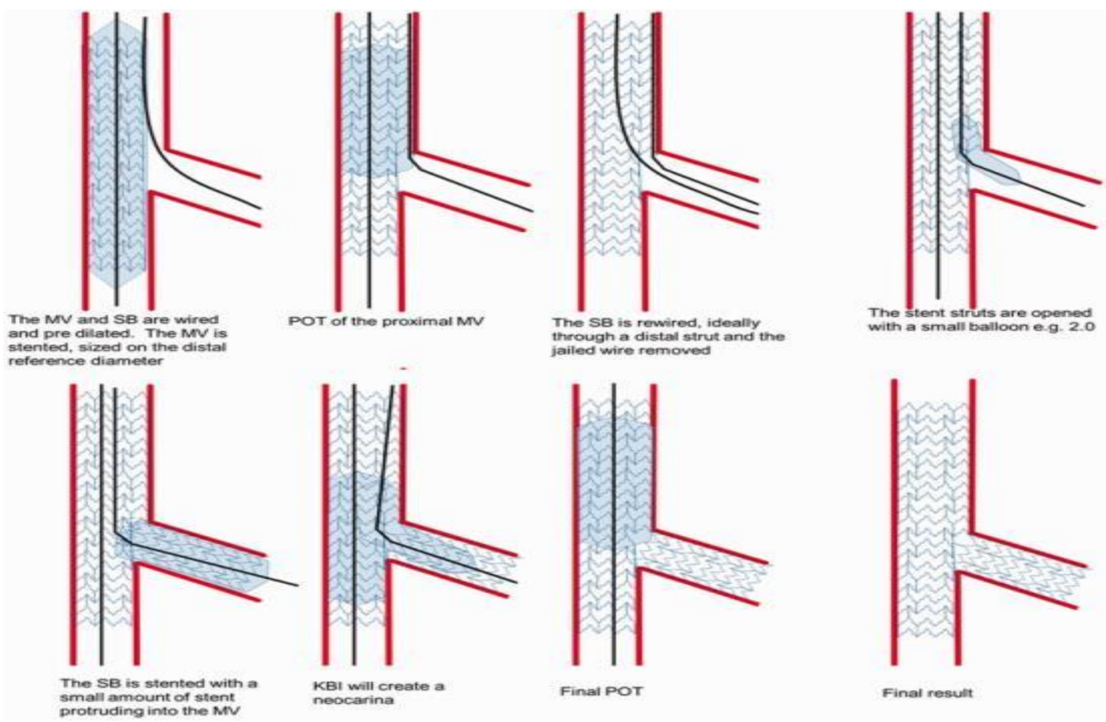

Figure (5): T stent/TAP, treating MV first. The first 4 steps of this procedure are the same as provisional stenting so this can be used as a bailout technique if there is a large dissection in the SB or compromise of SB flow, converting the provisional strategy to a T stent/TAP strategy **(37).**

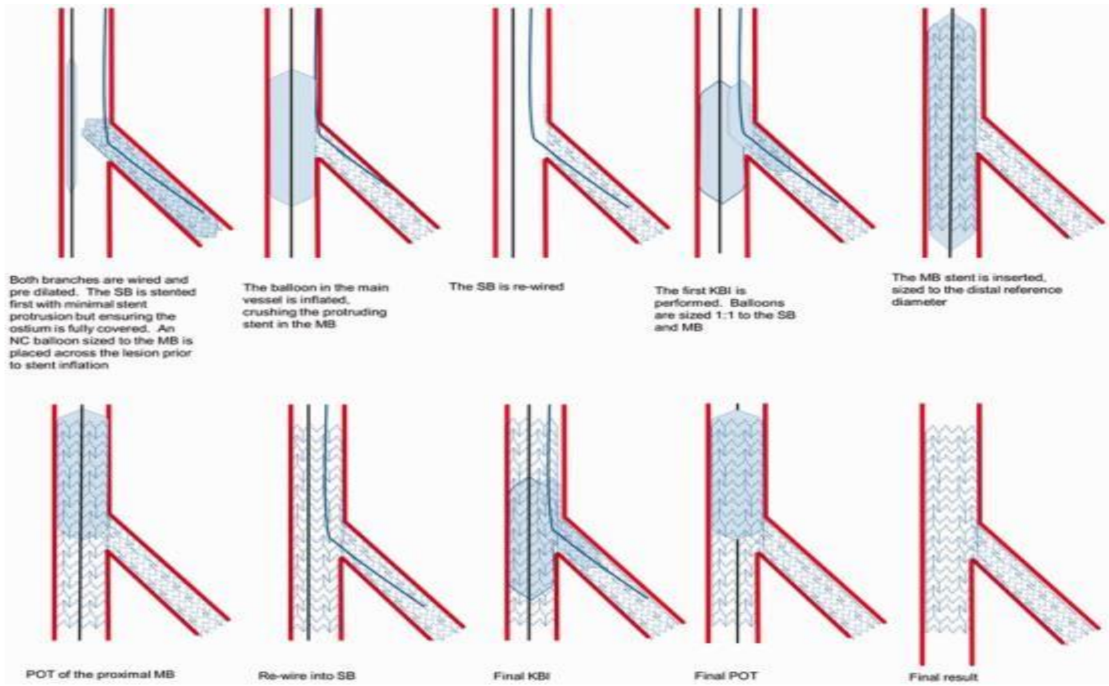

Figure (6): DK crush technique. This is the most complex of the bifurcation techniques. It has the advantage of maintaining wire access in the MV throughout. Two KBI (unlike classic or mini-crush) are performed which increases the success of re-cross after MV stenting **(37).**

Provisional Stenting vs. Two-Stenting Strategies:

The provisional versus two-stent strategy is determined by the SB and lesion complexity, as previously defined. Operators should be comfortable with at least one of the two-stent techniques (DK-crush, crush, T/T and small protrusion (TAP), and culotte), Both strategies should include the following techniques, which aim to reduce SB complications .

1. Wiring both the MV and SB
2. Meticulous lesion preparation
3. Intracoronary imaging pre- and post-PCI
4. Adequate stent length in the proximal MV to facilitate the proximal optimization technique (POT)
5. MV stent sizing 1:1 to the distal MV
6. Using noncompliant (NC) balloons sized 1:1 with the MV for POT and kissing balloon inflation (KBI)
7. Mandatory use of KBI for two-stent techniques but not for provisional techniques
8. Always finishing with a 1:1 POT in the proximal MV

POT is critical in both provisional and two-stent strategies to ensure proximal strut expansion and apposition, open stent cells across the SB, reduce the risk of abluminal rewiring, and facilitate SB recross. When utilizing a provisional strategy, a final POT with the distal balloon shoulder positioned at the level of the carina is still necessary (**25).**

Final KBI has not shown to improve outcomes in a provisional strategy, but it can be performed when the SB is compromised. Further interrogation with coronary physiology should be considered after provisional stenting if SB compromise is a concern.

When utilizing a two-stent strategy, the use of a DK-crush technique facilitates the recross with improved rates of final KBI and improved outcomes in LM bifurcations (**34).**

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