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STATE-OF-THE-ART REVIEW

Current Interventions for the Left Main Bifurcation

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ABSTRACT

Contemporary clinical trials, registries, and meta-analyses, supported by recent results from the EXCEL (Everolimus-Eluting Stents or Bypass Surgery for Left Main Coronary Artery Disease) and NOBLE (Percutaneous Coronary Angioplasty Versus Coronary Artery Bypass Grafting in Treatment of Unprotected Left Main Stenosis) trials, have established percutaneous coronary intervention of left main coronary stenosis as a safe alternative to coronary artery bypass grafting in patients with low and intermediate SYNTAX (Synergy Between Percutaneous Coronary Intervention With Taxus and Cardiac Surgery) scores. As left main percutaneous coronary intervention gains acceptance, it is imperative to increase awareness for patient selection, risk scoring, intracoronary imaging, vessel preparation, and choice of stenting techniques that will optimize procedural and patient outcomes. (J Am Coll Cardiol Intv 2017;10:849-65) © 2017 by the American College of Cardiology Foundation.

THE LEFT MAIN BIFURCATION

The incidence of left main coronary artery (LM) stenosis identified with coronary angiography is between 5% and 7% (1-3), and >80% of stenoses involve the LM bifurcation (LMB). The LM represents the largest coronary bifurcation, and stenting techniques are driven by potential complications to the left circumflex coronary artery (LCx) such as acute occlusion and long-term adverse outcomes of target vessel failure and target lesion revascularization (TLR) (4). In 75% of cases, the LM is >4.0 mm in diameter and averages 4.75 mm. Hence, the availability of large diameter stents and a clear understanding of the properties of current stent platforms to expand is required. Diffuse LM disease may conceal stenoses (5) and cause the vessel to appear disease free. The identification of diffuse LM disease should be suspected when the reference diameter of the LM is similar to the reference diameter of the left anterior descending coronary artery (LAD). The geometry reflected by Murray's branching law (6) indicates that the normal LM will always have a larger diameter. Adjunctive tools in the evaluation of the severity of LM stenosis include intravascular ultrasound (IVUS) and fractional flow reserve (FFR) (7).

SUPPORTING EVIDENCE FOR PERCUTANEOUS CORONARY INTERVENTION (PCI)

PCI VERSUS CORONARY ARTERY BYPASS GRAFTING (CABG) (ONLINE TABLE 1). The first LM PCI was performed by Andreas Grüntzig in 1978 (8). Five- to 10-year outcomes of LMB interventions have subsequently been evaluated in studies of PCI versus CABG (9-16), initially with bare-metal stents (17) and subsequently with drug-eluting stents (DES) (18-25). These studies have demonstrated comparative safety with low mortality and few major adverse cardiac and cerebrovascular events with both revascularization strategies. A higher incidence of cerebrovascular

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ABBREVIATIONS AND ACRONYMS

CABG = coronary artery bypass grafting

DES = drug-eluting stent(s)

DK = double kissing

FFR = fractional flow reserve

FKB = final kissing balloon

HRPCI = high-risk percutaneous coronary intervention

IABP = intra-aortic balloon pump

IVUS = intravascular ultrasound

KBI = kissing balloon inflation

LAD = left anterior descending coronary artery

LCx = left circumflex coronary artery

LM = left main coronary artery

LMB = left main coronary artery bifurcation

MACE = major adverse cardiac event(s)

MAE = major adverse event(s)

MB = main branch

MI = myocardial infarction

OCT = optical coherence tomography

PCI = percutaneous coronary intervention

POT = proximal optimization technique

PS = provisional stenting

RA = rotational atherectomy

SB = side branch

TAP = T-stenting with minimal protrusion

TLF = target lesion failure

TLR = target lesion revascularization

events was noted in the surgical group (9,26). In the SYNTAX (Synergy Between Percutaneous Coronary Intervention With Taxus and Cardiac Surgery) trial, compared with CABG, the LM PCI subgroup of patients with SYNTAX scores <33 who received first-generation DES had similar rates of major adverse cardiac and cerebrovascular events and death at 5 years, but significantly more patients (23%) in the DES group underwent TLR (9).

Second-generation DES were used in the EXCEL (Everolimus-Eluting Stents or Bypass Surgery for Left Main Coronary Artery Disease) (27) and NOBLE (Percutaneous Coronary Angioplasty Versus Coronary Artery Bypass Grafting in Treatment of Unprotected Left Main Stenosis) (28) trials. LMB stenosis was present in 81% of cases. The EXCEL trial randomized 1,905 patients with SYNTAX scores ≤32 to PCI with everolimus-eluting stents or CABG. There were fewer 30-day major adverse events (MAEs) with PCI compared with CABG (4.9% vs. 7.9%; $p = 0.008$) with low mortality (1% vs. 1.1%; $p = 0.82$) (27), signaling early procedural safety with PCI. At 3 years, the primary outcome of death, stroke, or myocardial infarction (MI) was similar between the 2 groups (15.4% vs. 14.7%; $p = 0.018$ for noninferiority, $p = 0.98$ for superiority); ischemia-driven revascularization was 12.6% for PCI and 7.5% for CABG ($p < 0.0001$). The presence of diabetes and chronic kidney disease did not influence outcomes.

The NOBLE trial (28) randomized 1,201 patients with LM stenosis, with an average SYNTAX score of 22.1 ± 7.7, to PCI or CABG. Similar early safety was seen, with low 30-day mortality with PCI (0.34%) and CABG (1.2%). However, at 5 years, PCI was inferior to CABG, with a higher rate of major adverse cardiac and cerebrovascular events (28.9% vs. 19.1%; $p = 0.0066$). Although death rates were similar (11.6% with PCI vs. 9.5% with CABG; $p = 0.77$), nonprocedural MI was more frequent with PCI (6.9% vs. 1.9%; $p = 0.004$). The rates of TLR were similar to those in EXCEL, at 12% in the PCI arm and 8% in the CABG arm ($p = 0.14$). In both these trials, repeat revascularization rates were lower (<13%) with second-generation DES compared with first-generation DES in the SYNTAX trial (23%).

It is important to consider that although the EXCEL trial has shown equivalent outcomes of PCI and CABG, its follow-up duration is only 3 years. The NOBLE trial demonstrated the superiority of CABG over PCI at 5 years. Consequently, until EXCEL reports 5-year follow-up data, true equivalence of PCI and CABG will be uncertain in this population.

GUIDELINES

Case selection and treatment options should follow guidelines, as outlined in Online Table 2.

The 2014 guidelines of the European Society of Cardiology assigned a Class Ib indication (the same as for CABG) to PCI for unprotected LM disease with a low SYNTAX score (<22) and a Class IIa indication for those with intermediate scores (23 to 32), whereas CABG was the preferred approach for patients presenting with high SYNTAX scores (>32) (29). The American College of Cardiology and American Heart Association 2014 guidelines give a Class IIa indication for LM PCI in patients with stable ischemic heart disease, low procedural risk, and SYNTAX scores <22 and a Class IIb recommendation for intermediate scores (22 to 32) (30). LM PCI should be rarely performed ad hoc, and for elective PCI, a heart team approach is strongly encouraged.

OPERATOR EXPERIENCE. LMB stenting should be performed by skilled operators familiar with techniques of LM stenting (31), at facilities that have access to intracoronary imaging (IVUS or optical coherence tomography [OCT]), coronary physiology, atherectomy, and mechanical circulatory support devices.

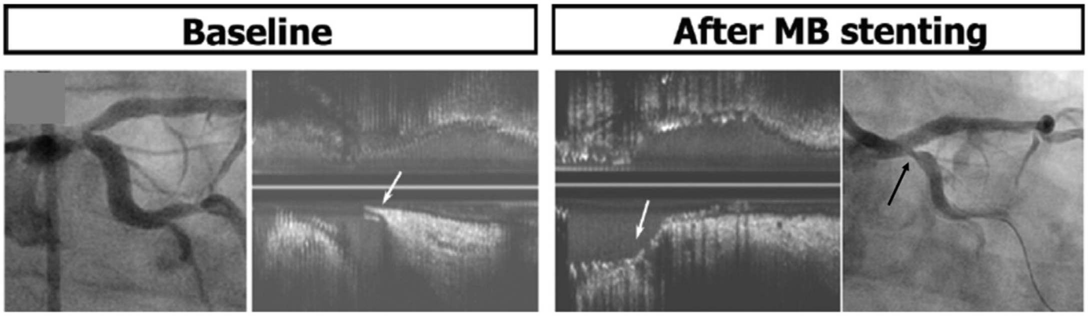
PRE-PROCEDURAL ASSESSMENT AND PLANNING OF LMB INTERVENTION

MEDINA CLASSIFICATION. The Medina classification (32–34) is an angiographic classification of bifurcation lesion complexity that assists in defining plaque distribution and procedural planning but does not predict outcomes of PCI. Medina classes 1,1,1, 1,0,1, and 0,1,1 denote true bifurcation lesions. The validity of this classification requires bifurcation dedicated quantitative coronary angiographic software.

IMAGING AND FUNCTIONAL ASSESSMENT. The size, angle, calcification, and length of the LM and daughter branches are assessed by diagnostic coronary angiography, IVUS or OCT and its functional significance by FFR in both daughter branches (LAD and LCx).

Imaging by IVUS or OCT can visualize plaque distribution, tissue characterization, arc of calcification (270° to 360°), and severity of stenosis. Criteria for LM

FIGURE 1 **Spiky Carina**



Left main bifurcation with a "spiky carina" or "eyebrow sign" at the ostium of the left circumflex **(white arrows)**. After main branch (MB) stenting, there is carinal shift and narrowing of the ostium of the left circumflex **(black arrow)**. Reproduced with permission from Suárez de Lezo J, et al. Predictors of ostial side branch damage during provisional stenting of coronary bifurcation lesions not involving the side branch origin: an ultrasonographic study. EuroIntervention 2012;7:1147-54.

intervention are: 1) LM lesion diameter stenosis $\geq$70% by angiography; 2) minimal luminal area (MLA) $\leq$6.0 mm^2 by IVUS or OCT; or 3) FFR $\leq$0.80 (27,35).

A limitation of OCT of the LM is the image interference with blood in a field that should be bloodless and filled only with contrast. Power injection of 20 ml of contrast over 5 s and a pressure of 500 psi can improve image quality (36).

Both IVUS and OCT can identify the pre-procedure "spiky" carina or "eyebrow" sign at the origin of the side branch (SB) that is a predictor of carinal shift and restenosis after LM stenting in a single-stent strategy (**Figure 1**).

ANATOMIC AND CLINICAL COMPLEXITY. The SYNTAX (37), SYNTAX II (38), NERS (New Risk Stratification II) (39), and EuroSCORE (European System for Cardiac Operative Risk Evaluation) (40) are the most widely used scores to describe anatomic and clinical complexity. The global risk score combines SYNTAX and EuroSCORE to provide an algorithm to identify low-risk patients who can benefit from CABG or PCI (41). The DEFINITION (Definitions and Impact of Complex Bifurcation Lesions on Clinical Outcomes After Percutaneous Coronary Intervention Using Drug-Eluting Stents) study (42) criteria are the only specific risk score for the LMB.

The SYNTAX score had prior validation (18,20, 43-45) for differential outcomes with PCI and CABG. However, in both EXCEL (27) and NOBLE (28), this score failed to clearly discriminate such outcomes, which might be attributed partially to different endpoints (and different DES) used in each trial.

THE BIFURCATION ANGLE. The bifurcation angle can be measured accurately by using computed tomographic angiography. A wide angle between the LM and LAD is associated with a reduced event rate after stenting because of less frequent TLR (46). However, the angle between the LAD and LCx did not predict clinical outcomes in the SYNTAX trial (47). A wide angle between the LAD and the LCx pre-PCI has been identified as a predictor of worse outcomes after the Culotte and classic crush techniques (48-50). However, in the DKCRUSH-III (Double Kissing Crush Versus Culotte Stenting for the Treatment of Unprotected Distal Left Main Bifurcation Lesions III) study, double kissing (DK) crush was associated with lower rates of major adverse cardiac events (MACEs) for the LMB when the bifurcation angle between the LAD and LCx was >70° compared with the Culotte stenting technique (15). Therefore, for wider bifurcation angles or when the LCx is smaller than the LAD (but larger than 2 mm), DK crush is the ideal 2-stent technique.

If the bifurcation angle is <70° and the LCx diameter is within 0.5 mm of the LAD diameter, either the Culotte or the DK crush technique can be performed (4,16).

HEMODYNAMIC SUPPORT FOR HIGH-RISK PCI (HRPCI). The global cVAD (Catheter Ventricular Assist Device) registry of Impella (Abiomed, Danvers, Massachusetts) utilization reported a 47% incidence of LM disease in patients with left ventricular ejection fraction <35% (51). PROTECT II (A Prospective, Multi-Center, Randomized Controlled Trial of the IMPELLA RECOVER LP 2.5 System Versus Intra Aortic Balloon Pump [IABP] in Patients Undergoing Non Emergent High Risk PCI) (52) was the only trial of left ventricular support in HRPCI that included LM intervention and compared the Impella 2.5 with an

IABP in patients with an average left ventricular ejection fraction of 24%. In-hospital mortality in the intention-to-treat population was 7.6% for the Impella and 5.9% for the IABP and 6.2% versus 6.9% for the per patient protocol.

The rate of MAEs was not different for patients with an IABP or the Impella at 30 days. However, at 90 days, trends for decreased MAEs were reported with the Impella compared with the IABP: 40.6% versus 49.3% ($p = 0.066$) in the intention-to-treat population and 40.0% versus 51.0% ($p = 0.023$) in the per patient protocol, with a relative risk reduction of 22%.

LM interventions with Impella support constituted 51% of cases in the USPELLA (US Impella) (53) registry, with an in-hospital death rate of 3.4%, 30-day mortality of 4%, a MACE rate of 8% in elective cases, and 12-month survival of 88%. Similarly, in the Europella (European Impella) registry (54), in-hospital mortality was 9.1%, 30-day survival was 94.5%, and the MACE rate was 12.4%. These outcomes resulted in U.S. Food and Drug Administration approval in 2015 of the Impella devices (2.5 and CP) for HRPCI (55). The Impella device is currently recommended for high-risk LM patients with depressed ejection fractions of <35%.

ACUTE CORONARY SYNDROMES. In the DELTA (Drug Eluting Stents for Left Main Coronary Artery Disease) registry, 13.9% (379 patients) had acute coronary syndromes, of whom 61 presented with ST-segment elevation MI and the rest with non-ST-segment elevation MI. Of the 379 patients, 279 underwent stenting with first-generation DES and the rest CABG. IABPs were used in <13% of cases. At 3 years, there were comparable outcomes between PCI and CABG (56).

ACCESS AND GUIDING CATHETERS. LM PCI can be performed by either femoral or radial access with 6-F extra backup (EBU) 3.5/3.75 or Judkins JL 3.5/4-F guiding catheters (with side holes) if the LM ostium is diseased. Seven- or 8-F guiding catheters can be used for large-caliber coronary arteries, rotational atherectomy (RA) burr sizes >1.75 mm, or rarely if 2 stents must be delivered simultaneously.

LMB INTERVENTION

AN ALGORITHM FOR LMB INTERVENTION IS PROVIDED IN THE CENTRAL ILLUSTRATION. There are differences between the European approach with the Main Across Distal Side (MADS) treatment strategies (34) as proposed in the European Bifurcation Club consensus document in 2015 and the Asian Bifurcation Club approach as proposed at the Nanjing Left Main & Coronary Bifurcation Summit in 2016. However, the consensus is that initial PS approach with a single-stent strategy should be preferred when possible, as validated recently in the EXCEL (27) and NOBLE (28) trials.

SIMPLE VERSUS COMPLEX LESION. To stratify the best LM stenting strategy, LMBs are classified as simple or complex on the basis of the criteria in the DEFINITION study (42).

A simple LMB lesion has SB diameter stenosis <70% and lesion length <10 mm. This is seen in 75% of cases and can be treated with a single-stent provisional approach.

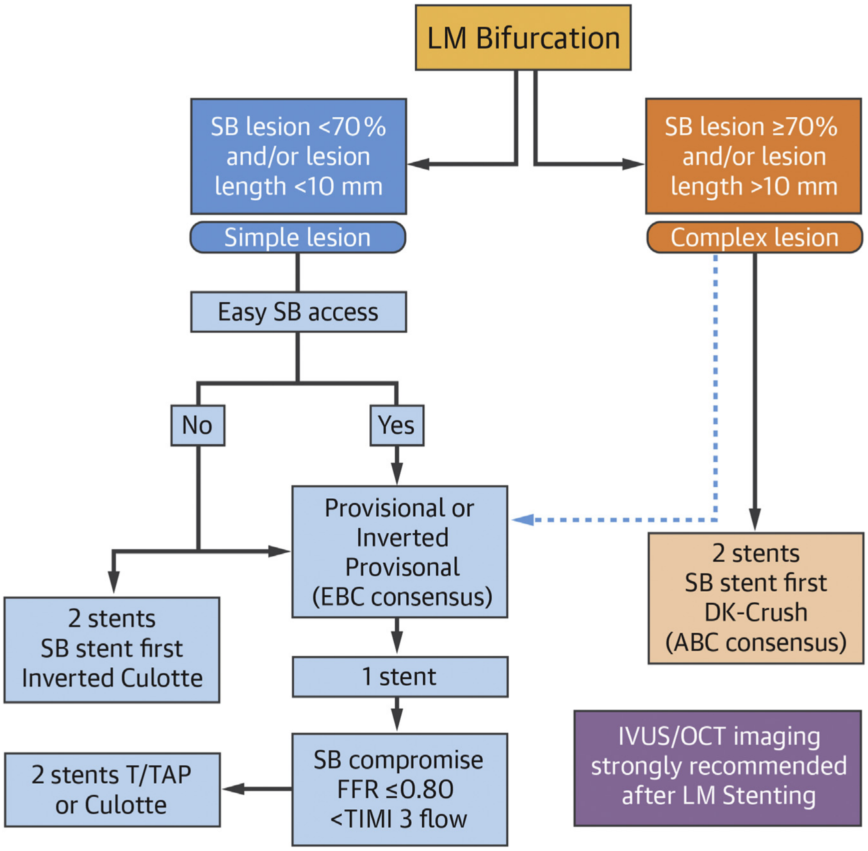
A complex LMB lesion has SB diameter stenosis >70% and lesion length >10 mm. A simple lesion can change to a complex lesion with the presence of 2 of the following 6 minor criteria (42): 1) moderate to severe calcification; 2) multiple lesions; 3) LAD-LCx bifurcation angle >70°; 4) main vessel reference vessel diameter <2.5 mm; 5) thrombus-containing lesion; and 6) main vessel lesion length >25 mm. Complex lesions generally require a 2-stent strategy.

MAIN BRANCH (MB) AND SB WIRING. Both branches should be wired, with the most difficult branch wired first. The second wire is then inserted while limiting the rotation maneuver to avoid wire wrap. Wiring the SB (the LCx) provides a safety net in case of abrupt occlusion, generally in ostial SB disease of >50%. It also facilitates flow recovery by acting as a marker for rewiring the SB (57). The SB wire helps change the bifurcation angle, which can facilitate access to the SB during guidewire exchange. In our opinion, an SB <2.0 mm should be wired but not intervened on.

Microscopic evaluation suggests that polymer-coated wires, when jailed, are more resistant to retrieval damage and more efficient in crossing the SB ostium than non-polymer-coated wires (58).

LESION PREPARATION AND THE CALCIFIED VESSEL. Noncompliant and scoring balloons are mostly used to optimize lesion preparation for stent delivery. Rotational atherectomy (RA) is required for non-dilatable or severely calcified LM lesions. In the PROTECT II trial, RA was used in 8% of cases in the Impella arm versus 3.1% in the IABP arm. RA averaged 5 passes, with total RA time of 60 s in the Impella arm and 40 s in the IABP arm, and was associated with increased rates of MI (13.8% vs. 10.4%). Adverse events can be reduced with short-duration RA at a speed of 140,000 to 180,000 rpm with <3 passes and burr advances of <10 s using burr sizes of 1.5 and 1.75 mm (59). Caution should be exercised in

CENTRAL ILLUSTRATION **Algorithm for Left Main Bifurcation Intervention**



Rab, T. et al. J Am Coll Cardiol Intv. 2017;10(9):849-65.

ABC = Asian Bifurcation Club; DK = double kiss; EBC = European Bifurcation Club; FFR = fractional flow reserve; IVUS = intravascular ultrasound; LM = left main coronary artery; OCT = optical coherence tomography; SB = side branch (generally the left circumflex); TIMI = Thrombolysis In Myocardial Infarction; T/TAP = T-stenting or T-stenting and minimal protrusion.

angulated lesions, in which wire bias can cause vessel perforation. In a small series of patients who had RA performed in calcified unprotected LM stenosis, TLR rates were <20% at 2 years (59,60). Temporary pacing is recommended in HRPCI with low ejection fraction when RA is used.

ONE VERSUS 2 STENTS. There is a lack of randomized studies comparing 1- and 2-stent techniques for LMB.

The COBIS (Coronary Bifurcation Stenting) II registry (61) reported a higher incidence of cardiac death, MI, and target lesion failure (TLF) after double-stenting for LMB lesions. The DKCRUSH-III study (15,16) is the only randomized, multicenter 2-stent study that compared DK crush with Culotte stenting for patients with distal LMB lesions. At 3-year follow-up, Culotte stenting was consistently associated with an increased MACE rate (23.7% vs. 8.2%; $p < 0.001$), driven mainly by increased stent thrombosis (3.9% vs. 0.5%; $p = 0.02$), MI (8.2% vs. 3.4%; $p = 0.037$), and target vessel revascularization (18.8% vs. 5.8%; $p < 0.001$), especially in complex LMB lesions.

The DEFINITION study (42) provided evidence that for complex LMB lesions, 2 stents were associated with improved clinical outcomes compared with a 1-stent strategy.

The ongoing EBC MAIN (European Bifurcation Club Left Main Study) (NCT02497014) (62) randomized trial comparing 1 versus 2 stents (DK crush or Culotte) and the DKCRUSH-V randomized trial comparing PS with the DK crush technique will provide important information on the optimal treatment of LMB lesions.

CHOICE OF TECHNIQUES FOR LMB STENTING

SINGLE-STENT STRATEGY. PS (Figure 2). Randomized studies suggest that the provisional SB stenting strategy is superior and should be the recommended strategy (63,64). In a subgroup of the SYNTAX trial, there was a lower rate of cardiac death at 3 years (65) and a lower 1-year MACE rate (47) with a PS approach. Ten-year follow-up of a large propensity-matched group of patients showed that patients treated with PS of LMB lesions had comparable rates of TLR compared with a 2-stent strategy (19,22). A meta-analysis of 7 observational studies using DES for LM stenting with 1 versus 2 stents demonstrated a decreased MACE rate (20.4% vs. 32.8%) (odds ratio: 0.51; 95% confidence interval: 0.35 to 0.73) and TLR or target vessel revascularization (10.1% vs. 24.3%; odds ratio: 0.35; 95% confidence interval: 0.25 to 0.49) (66) with a single-stent approach.

PS (33) with a single-stent crossover from the LM into the LAD or the MB is the most common strategy in 75% LMB interventions (27,28). LMB with nonsignificant ostial LCx stenosis of $<50\%$ with a lesion length of <5 mm, a non-left-dominant coronary system, or an LCx <2.0 mm in diameter favors a 1-stent approach. If the predominant lesion is in the LCx and the ostium of the LAD is not diseased, a provisional 1-stent approach can be directed from the LM toward the LCx (inverted provisional).

Optimal visualization of the LMB and SB ostium is achieved in left anterior oblique caudal (spider view) and anteroposterior or right anterior oblique caudal projections. The diameter of the LM stent must be carefully selected according to the diameter of the distal vessel (LAD). If an oversized stent is selected, it will not only increase the risk for distal dissection but also the risk for carinal shifting, which may result in SB occlusion. The proximal optimization technique (POT) is then performed (described later). This allows strut protrusion into the SB with a larger strut opening, as well as no or limited carinal shifting for easier guidewire exchange. There are 3 options for the SB. 1) For the simple lesion, crossover stenting followed by the POT with no SB dilatation or kissing balloon inflation (KBI) is recommended. 2) If intervention is required to the SB, guidewire exchange occurs. The MB wire is pulled back and inserted into the SB through the most distal cell (closest to the carina), thus allowing the projection of struts in the ostial segment of the SB opposite the carina. The jailed SB wire is then pulled back and placed in the MB. An alternative technique using a fresh wire is to create a gentle double curve at the tip, crossing the LM into the LAD with the tip pointing upward and then gently pulling back with tip rotation downward to enter the SB. The POT, KBI, and re-POT is then performed. Or 3) POT SB inflation and re-POT is then performed without KBI (67,68). This optimizes the result of PS by maintaining circular geometry and reduces SB ostium strut obstruction allowing access to the LCx, the risk for SB occlusion, and global strut malapposition.

If the result of the SB is inadequate after MB stenting with TIMI (Thrombolysis In Myocardial Infarction) flow grade <3 or FFR <0.80 (7,69), a second stent can be placed by the T-stenting/TAP or Culotte technique (70) after guidewire exchange (**Figures 3 and 4**).

Special care should be taken during LM stenting to avoid longitudinal stent compression. Pull-back of the jailed wire or a partially deflated balloon may deep-seat the guiding catheter and damage the stent. Optimal control of the guide with the left hand is thus crucial to avoid this complication (**Figure 5**).

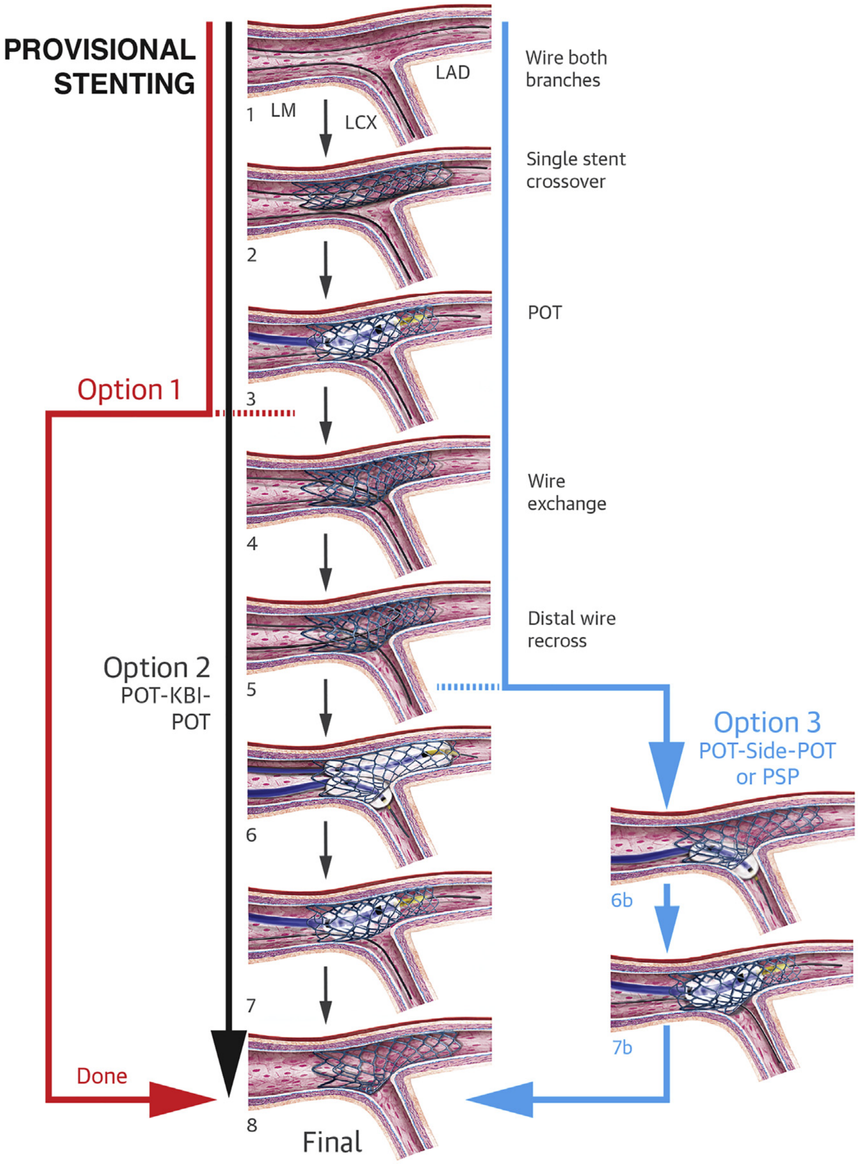
POT. The POT provides the LM crossover stent 2 distinct diameters corresponding to the diameters of the 2 covered segments (LAD and LM) that were derived by Murray's law (71). This technique allows the reconstruction of the initial physiological anatomy of the bifurcation and follows the fractal law of Finet (72):

$$\text{LM final stent diameter} = (\text{diameter of LAD} + \text{diameter of LCx}) \times 0.67$$

POT facilitates wire exchange, when SB treatment is needed by avoiding abluminal wire exchange outside the proximal part of the stent (73). The stent should be implanted sufficiently proximal to the SB to accommodate a short, large-diameter balloon sized to the LM and at least 6 or 8 mm in length. Online Table 3 illustrates the expansion profiles of different stent types to accommodate the large LM caliber (74). The distal marker of this balloon must be positioned in front of the carina. Optimization of the proximal stent segment allows strut protrusion into the SB with a larger strut opening, as well as no or limited carinal shifting for easier guidewire exchange, optimization of the stent diameter to the LM diameter, correcting malapposition, and reducing ellipticity of the stented segment (68).

KBI in PS. Routine KBI in the MB and SB after PS has failed to provide clear clinical benefits (75–80). During 2-year follow-up, the rate of the composite of death, MI, or TLR was not significantly different between KBI and no KBI, regardless of angiographic SB stenosis (12.5% in the final kissing balloon [FKB] group

FIGURE 2 **Provisional Stenting With Single Stent Crossover**

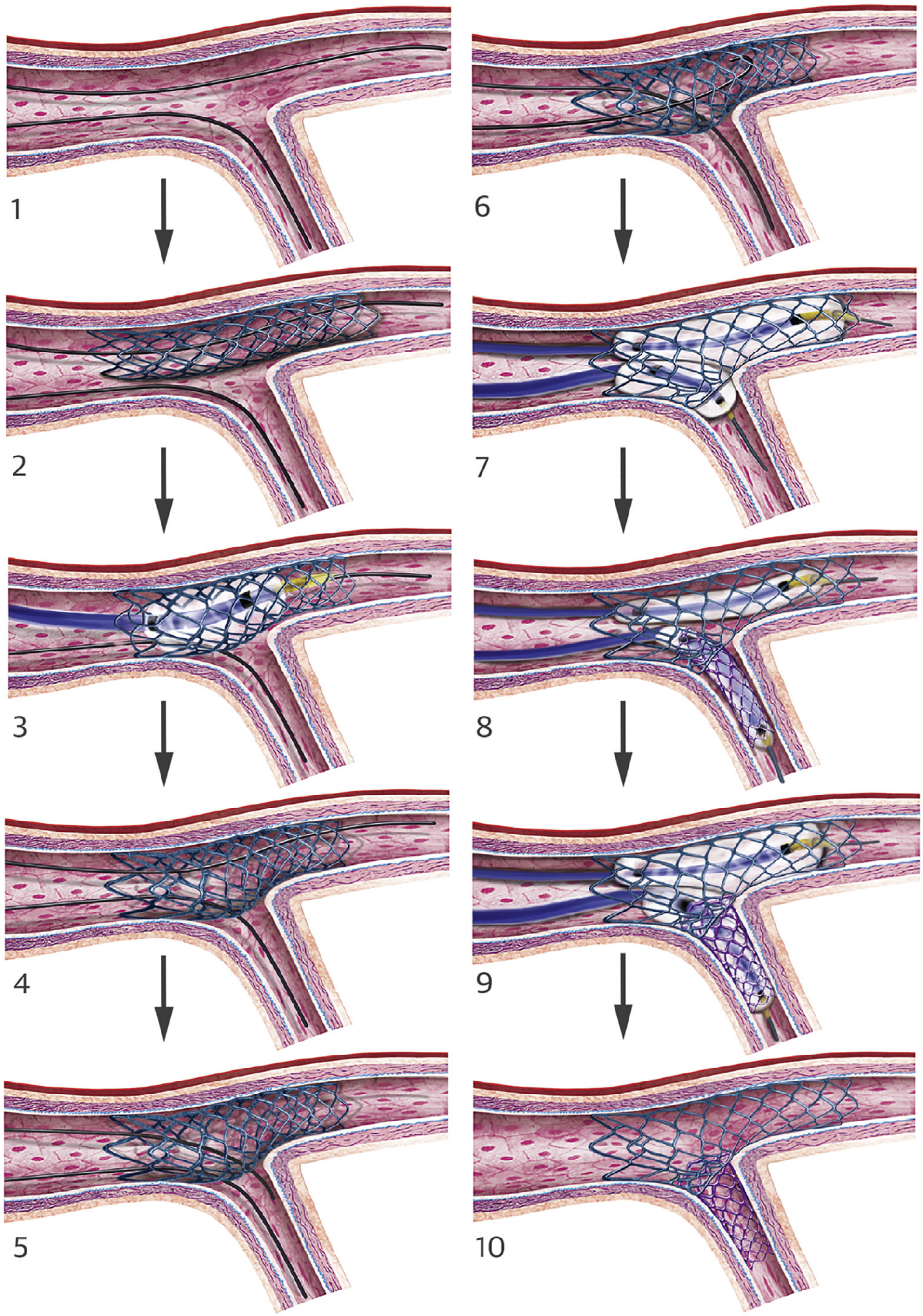


Provisional stenting with a single stent crossover technique: **(1)** Insertion of a wire into each branch. **(2)** Stenting of the main branch (left main coronary artery [LM] to left anterior descending coronary artery [LAD]) with diameter selected according to the diameter of the LAD. **(3)** The proximal optimization technique (POT) with a short balloon with diameter adapted to LM diameter with the tip marker ending in front of the carina. In option 1, the procedure can end if the result is acceptable **(8)**. If intervention is required to the ostium of the side branch (SB) (option 2), guidewire exchange is performed **(4)**. The jailed wire is withdrawn carefully to avoid abrupt guiding catheter intubation and subsequently advanced into the distal main branch. **(5)** There is distal recross (closest to carina) with main branch wire or a new wire. Kissing balloon inflation (KBI) is carried out with 2 short, preferably noncompliant balloons with the SB balloon minimally extending beyond the ostium. The balloons should have diameters compatible with both distal branches **(6)**. Re-POT is performed **(7)** with final result **(8)**. In option 3, after step 5, SB opening using a short noncompliant balloon **(6b)**. Re-POT to restore stent distortion opposite to the SB **(7b)** with final result **(8)**. LCX = left circumflex coronary artery.

and 8.5% in the non-FKB group). Five-year follow-up of the DKCRUSH-II study demonstrated that in the PS group, TLR with FKB was 19.4% compared with 5.2% without FKB ($p = 0.31$) (81).

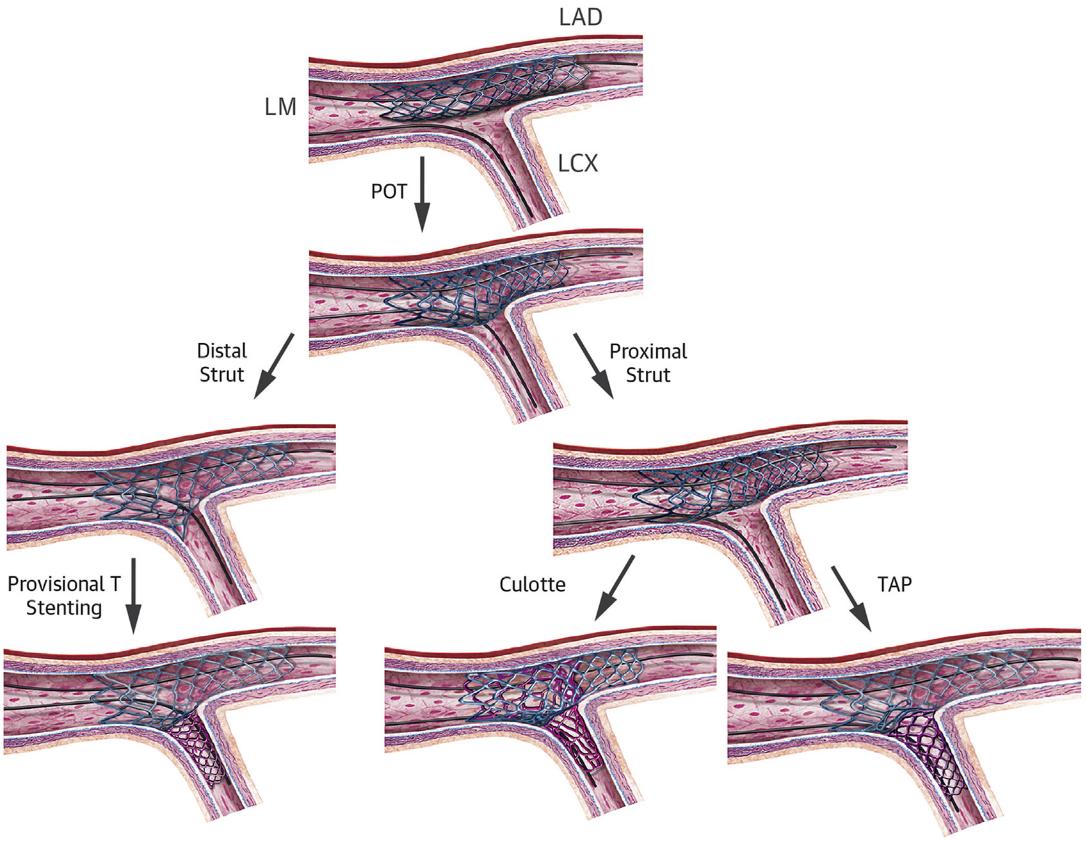
When necessary and to prevent potentially negative effects of KBI (76–79,82) (after rewiring the LCx through the distal portion of the cell overlying the SB), short noncompliant balloons are used in the

FIGURE 3 **T-Stenting and Minimal Protrusion**



As in provisional stenting. **(1)** Insertion of a wire into each branch. **(2)** Stenting of the main branch (left main coronary artery [LM] to left anterior descending coronary artery [LAD]), with diameter selected according to the diameter of the LAD. **(3)** The proximal optimization technique with a short balloon with diameter adapted to LM diameter with the tip marker ending in front of the carina. If intervention is required to the side branch (SB), guidewire exchange is performed **(4)**. The jailed wire is withdrawn and advanced into the LAD. **(4, 5)** There is distal recross (closest to carina) with main branch wire **(6)**. Kissing balloon inflation (KBI) or a single balloon inflation is performed to open SB struts **(7)**. The SB stent is delivered through the opened struts with minimal protrusion into the LM **(8)**. High-pressure inflation of SB stent followed by KBI **(9)**. Final result with minimal SB stent protrusion into the LM **(10)**.

FIGURE 4 **Choices for Second Stent in Provisional Stenting**

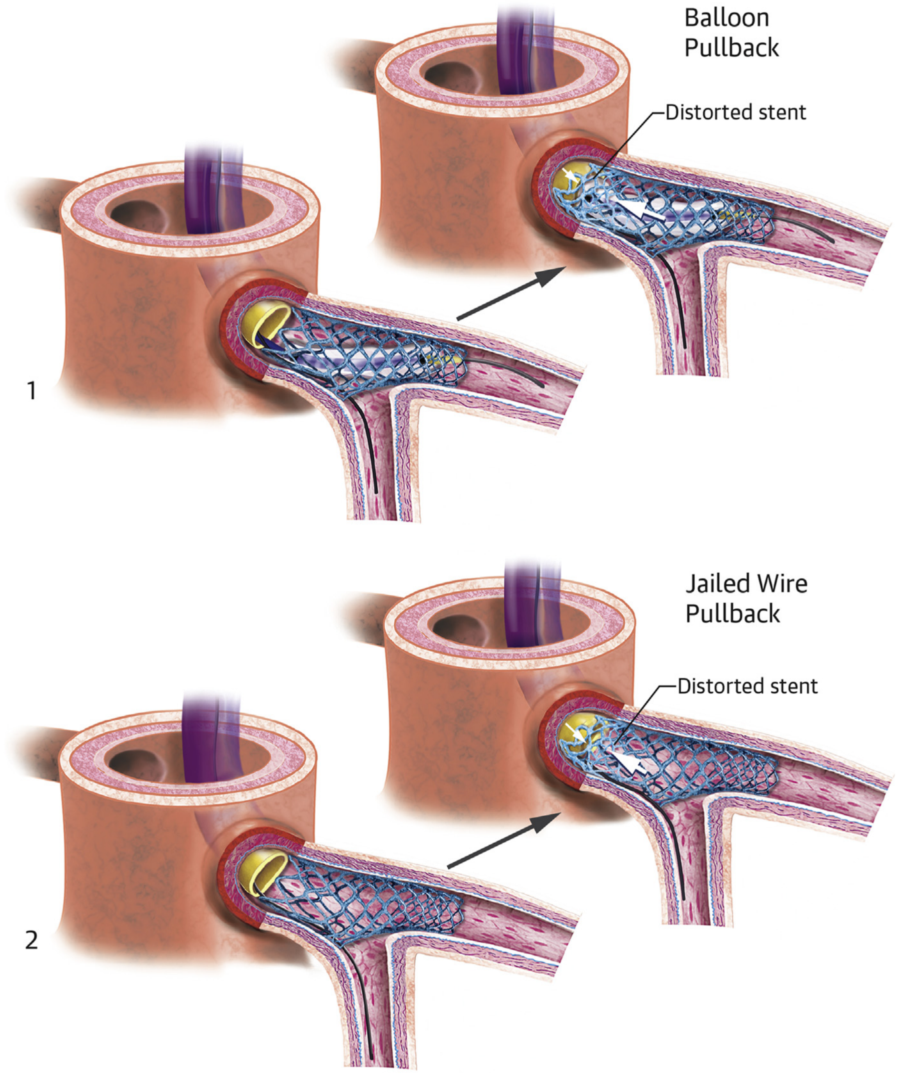


After the proximal optimization technique (POT), the stent is fully apposed in the distal main branch and proximal main branch **(top)**. If the main branch wire is inserted in the side branch (SB) in a strut close to the carina **(bottom left)**, the SB ostium is covered by the main branch stent after kissing balloon inflation (KBI), and an SB stent is not needed in the majority of cases. If an SB stent is necessary (dissection, long lesion), T-stenting can be done **(bottom left)**. In case of access through a more proximal strut **(bottom right)**, the SB ostium is not covered by the main branch stent after KBI. If an SB stent is needed, the 2-stent technique should be T-stenting and minimal protrusion (TAP) or a Culotte to cover the SB ostium. LAD = left anterior descending coronary artery; LCX = left circumflex coronary artery; LM = left main coronary artery.

unstented SB to prevent the occurrence of dissection and to avoid oval distortion in the LM. Balloon diameters are chosen according to Murray's law, and balloon inflation occurs in the SB first with simultaneous deflation. To reduce proximal stent deformation when relatively long balloons are used, a "modified KBI approach" was recently proposed (67,75) using asymmetrical inflation pressures: the SB is first inflated to 12 atm, then partly deflated back to 4 atm, with subsequent simultaneous inflation of both balloons at 12 atm with simultaneous deflations. Routine KBI is not recommended for a single-stent strategy, but FKB is mandatory for 2-stent techniques, including the PS strategy that converts to a 2-stent technique.

CONVERSION TO A 2-STENT STRATEGY. T-stenting and TAP (Figures 3 and 4). T-stenting or TAP is used to optimize the SB in the setting of PS when the initial strategy was a planned 1-stent approach. However, operators increasingly perform it as their go-to technique when an elective double-stenting strategy is required (83). The LM stent is sized to the distal vessel, and the POT is performed. The jailed SB wire is withdrawn, and the SB is recrossed through a distal cell (closest to the carina). An anticipated pitfall of this technique is that a single-layer "neocarina" is created by the SB stent struts protruding inside the LM at the level of the carina. The SB takeoff angle and site of strut crossing are major determinants of neocarina length. When the SB has a T-shaped takeoff, small SB stent

FIGURE 5 **Two Mechanisms of Stent Longitudinal Distortion When Stenting the Left Main Coronary Artery**

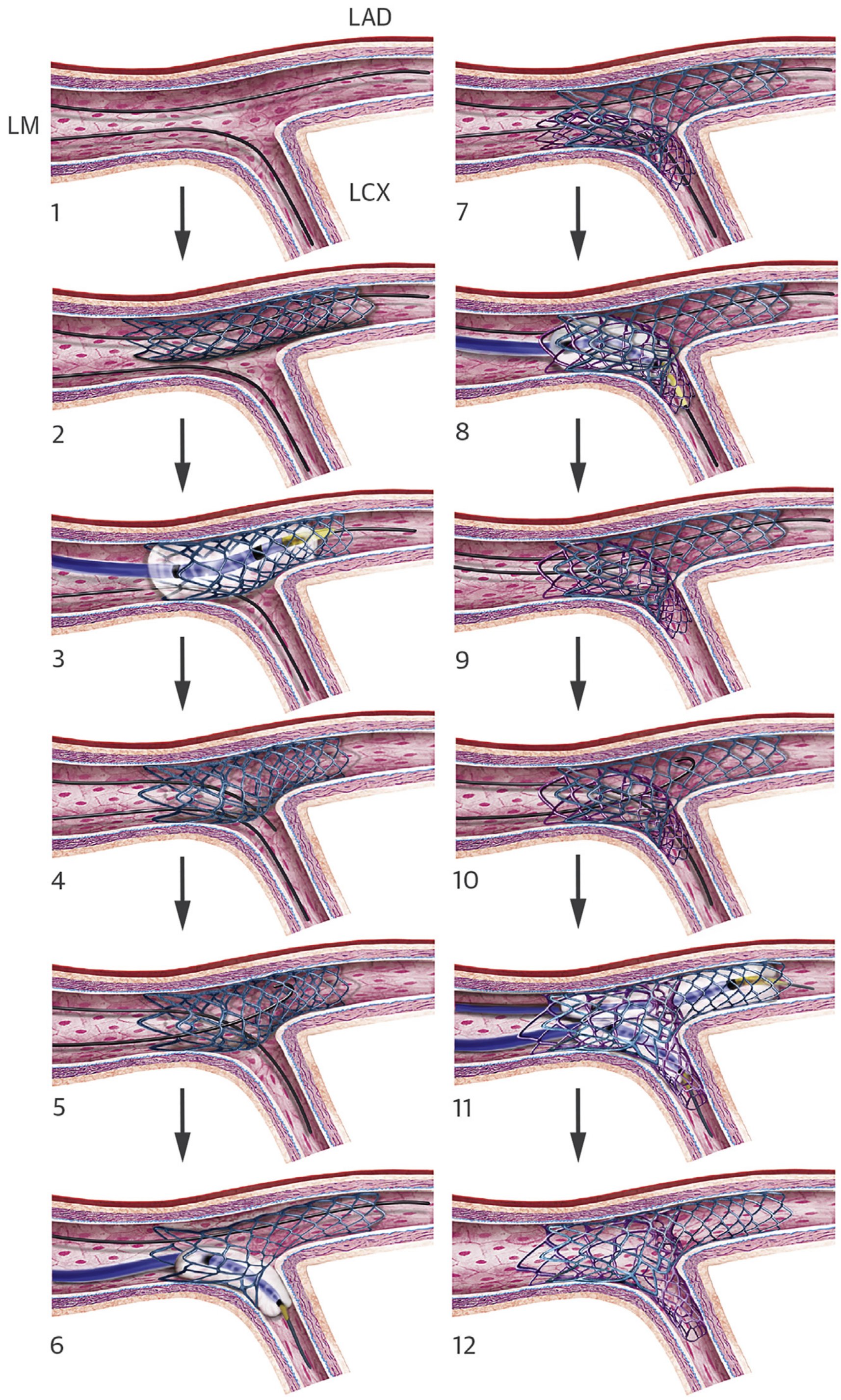


(1) The balloon delivery system or post-dilatation balloon is pulled back too early after deflation. **(2)** Pull-back of the jailed wire may deeply intubate the guiding catheter and damage the stent. Optimal control of the guide with the left hand is crucial. Modified with permission from Sawaya FJ, Lefèvre T, Chevalier T, et al. Contemporary approach to coronary bifurcation lesion treatment. J Am Coll Cardiol Intv 2016;9:1861–78.

protrusion inside the LM is needed to cover the SB ostium successfully. In contrast, acute SB angles (Y shapes) are associated with longer, oval-shaped SB ostia, which implies the need for wider protrusion of the SB stent inside the LM, resulting in a longer neocarina. For such reasons, striving to limit protrusion while implanting the SB stent is critical. KBI is the final step of the TAP technique. Deflations should be simultaneous, otherwise the protruded stent in the LM will keep the same position as before KBI. In a recent study of 57 de novo LMB lesions, TAP stenting with second-generation DES had acceptable TLF rate at 3-year follow-up of 13.3% (84). In contrast, the BBK (Bifurcations Bad Krozingen) II study, in which 39% underwent LM stenting, the Culotte technique compared with TAP at 1 year had a TLF rate of 6.7% versus 12.0% ($p = 0.11$) (85).

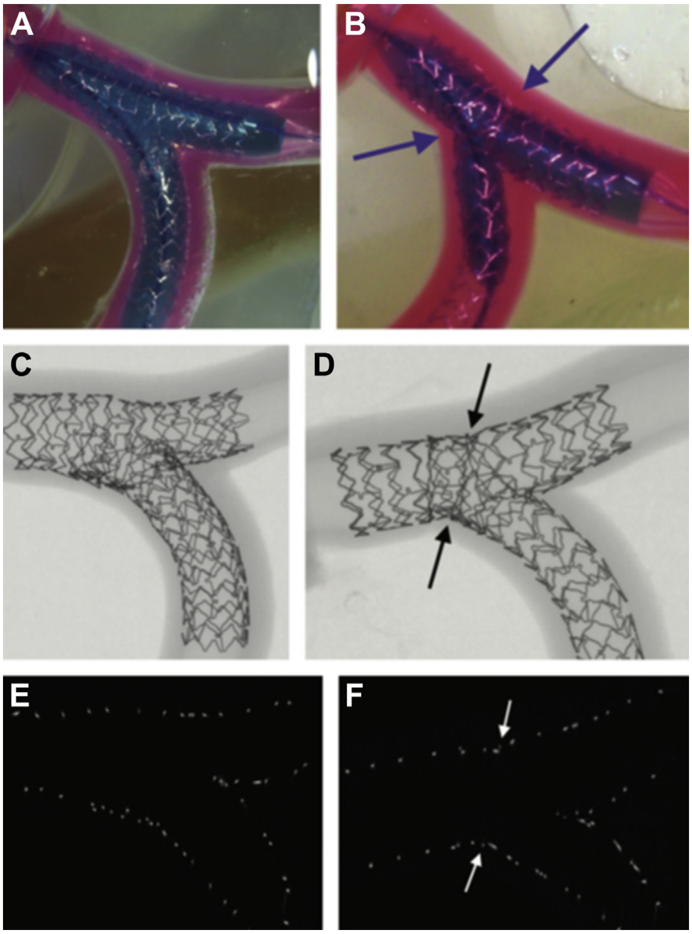
Culotte stenting (Figure 6). The original Culotte stenting (70) using bare-metal stents had been largely abandoned because of high restenosis rates. Since the introduction of DES, Culotte stenting has regained its popularity (inverted Culotte is the same technique

FIGURE 6 **Culotte Technique**



(1) Insertion of a wire into each distal branch. **(2)** First stent deployed in the main branch sized to the left anterior descending coronary artery (LAD). **(3)** First proximal optimization technique (POT) performed. **(4, 5)** Wire exchange performed. **(6)** Balloon dilatation of stent struts into side branch (SB). **(7)** Second stent deployed from the SB into the main branch using stent diameter according to the distal SB reference. **(8)** Second POT. **(9, 10)** Second wire exchange. **(11)** Kissing balloon inflation. **(12)** Final result. LCX = left circumflex coronary artery; LM = left main coronary artery.

FIGURE 7 Inferior Results After Final Kissing Balloon Inflation in Culotte Stenting Compared With Double Kissing Crush Stenting of Left Main Coronary Artery Bifurcation



Final kissing balloon inflation of double kissing (DK) crush stenting **(A, C)**. Culotte stenting: significant "napkin ring" restriction (stent underexpansion) at either the side branch or main branch ostium with Culotte technique **(arrows) (B, D)**. Stent underexpansion with Culotte at left main coronary artery bifurcation **(F) (arrows)** versus DK crush **(E)**.

with the first stent from the LM to the SB). In an in vitro study of Culotte stenting (86), proximal SB recrossing as opposed to optimal distal SB recrossing resulted in more unopposed struts at the ostium, a neostent carina formation, and reduction of the strut-free SB ostial area. Stent underexpansion was recognized as an independent predictor of stent thrombosis and restenosis with restriction of stent expansion like a "napkin ring" with Culotte stenting (Figure 7) using closed-cell stents (75). However, even with open-cell stents in LMB lesions, significant stent underexpansion either in the LM or SB ostium was noted with Culotte stenting in contrast to DK crush stenting (15,16).

INTENTIONAL 2-STENT TECHNIQUE. DK (Double Kiss) crush stenting (15,16) (Figure 8). DK crush stenting (87), a modification of the classic crush technique, has gained popularity as the preferred 2-stent LM technique for the complex LMB lesion.

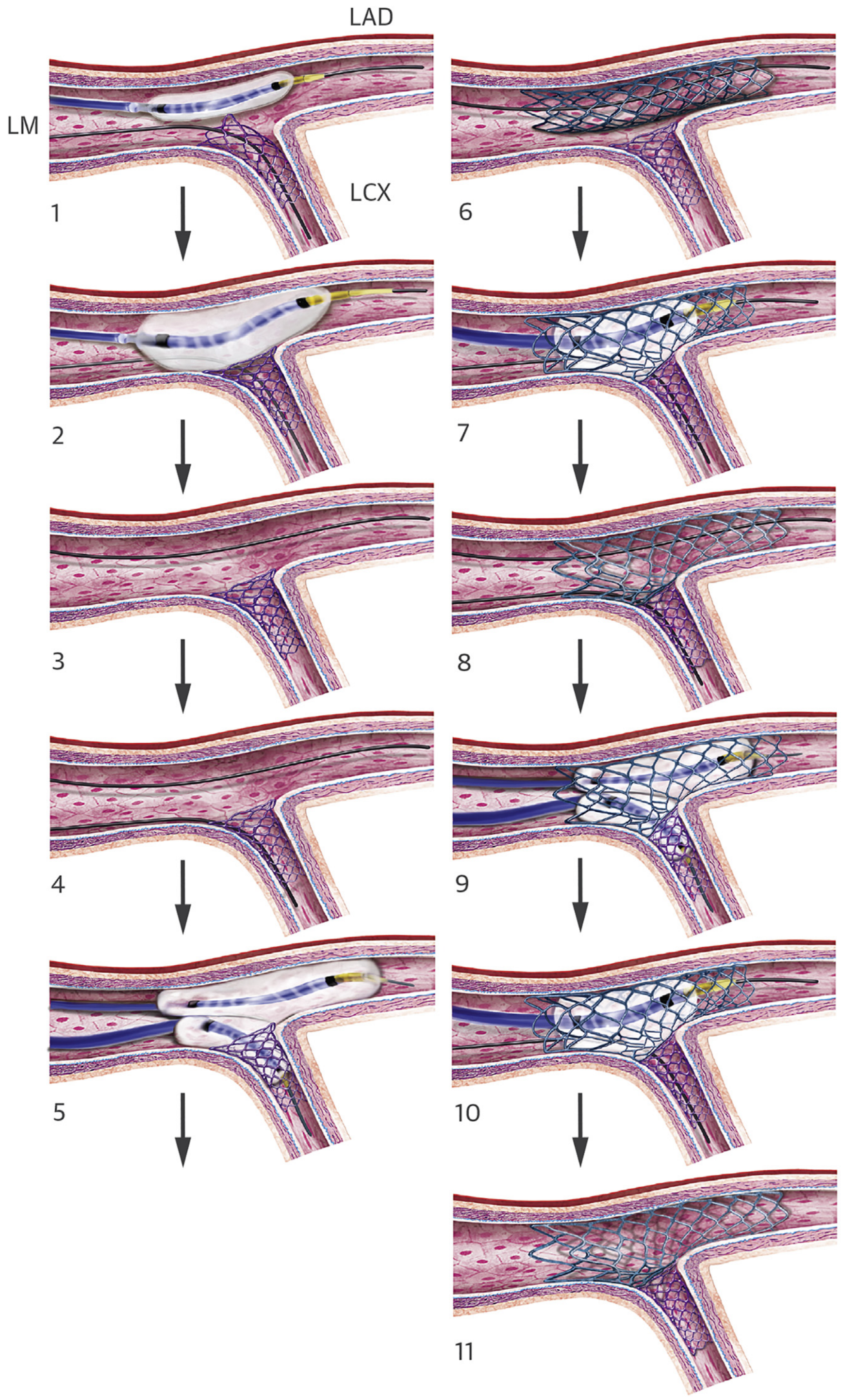
The main difference between classic and DK crush is the use of first KBI. After balloon crush of the implanted SB stent, which protrudes minimally into the LM, there are 2 layers of stent struts at the ostial SB. First KBI optimizes the distorted SB stent, leaving only 1 layer of metal struts at the ostial SB while minimizing repeated distortion of the ostial SB stent with LM stent deployment and facilitates the final KBI after LM stenting. Careful attention should be paid to rewiring the SB from the proximal stent cell, as distal SB recrossing increases the possibility of the coronary guidewire traversing the abluminal area between the stent and the vessel wall, leaving a significant gap at the SB ostium after final KBI. The methods to confirm the exact position of the SB wire are as follows: visual assessment from fluoroscopy (orthogonal projections to confirm SB rewiring from the proximal stent cell (away from the carina) and or guidance with IVUS or OCT from the main vessel.

POST-PROCEDURE IMAGING AND PHYSIOLOGICAL ASSESSMENT

Post-procedure imaging with IVUS or OCT is strongly recommended. This should be performed both from the LAD and LCx to the LM. Imaging can identify incorrect stent expansion or apposition, dissections, or significant residual disease, which might go undetected on conventional angiography (88,89). OCT provides exquisite detail of stent apposition, coverage, and proximal (with DK crush) or distal SB guidewire crossing (with TAP and Culotte techniques) before balloon inflations.

At 3 years, in patients receiving DES for LM lesions, a mortality benefit was seen with IVUS guidance compared with angiographic guidance (4.7% vs. 16.0%) (88). In a pooled analysis of 4 registries, there was 90% survival when IVUS was used for LM stenting versus 80.7% in the no-IVUS group ($p = 0.03$) (90). Randomized trials, however, have failed to show a clinical benefit of IVUS use (91,92). Optimal results are seen when there is restoration of fractal LM anatomy as derived from Finet's (72) formula. Mean stent areas assessed by IVUS of 8.2 mm^2 in the body of the LM, 7.2 mm^2 at the bifurcation, 6.3 mm^2 in the proximal LAD, and 5.0 mm^2 in the proximal LCx are associated with better outcomes. An ostial LCx mean stent area <4 mm^2 confers increased thrombotic and restenosis risk (89,93). Criteria for optimal stent

FIGURE 8 **Double Kissing Crush or DK Crush Technique**



(1) Side branch (SB) stenting with short main branch protrusion of 2 to 3 mm. Balloon maintained in main branch across SB ostium. **(2)** SB stent balloon crush by main vessel balloon. **(3)** SB wire withdrawal. **(4)** SB wire proximal recrossing. **(5)** High-pressure dilatation of SB ostium followed by first kissing balloon inflation. **(6)** Main branch stenting across the SB after SB wire is removed. **(7)** Proximal optimization technique (POT). **(8)** Second SB wire recrossing through the main branch stent and the crushed SB stent. **(9)** Sequential balloon inflations to 16 atmospheres followed by second kissing balloon inflations to 12 atmospheres each, followed by simultaneous deflations. **(10)** Re-POT. **(11)** Final result. LCX = left circumflex coronary artery; LM = left main coronary artery.

implantation are also applicable to OCT, which is superior to angiography (94). FFR is used to assess SB hemodynamic compromise post-PCI when a residual angiographic stenosis is seen post-intervention (69).

OSTIAL AND MIDSHAFT STENOSIS

Ostial and midshaft stenosis has better clinical outcomes with DES than LMB stenting, as seen in the DELTA registry. At 3 years, the rate of MACEs was 19.1% compared with 28.5%, the rate of target vessel revascularization was 9.3% compared with 17.7%, and the rate of TLR was 4.5% compared with 12.6% (95).

TRIFURCATIONS

Trifurcations are encountered in 10% of cases (96,97) and pose technical challenges. In these cases, a single-stent strategy is recommended. If SBs have limited disease, “triple kissing” balloon inflations, or “trissing,” is associated with favorable early and long-term results (97). When significant SB disease is present, any 2-stent technique might be used according to the specific anatomy; a minor SB (LCx or ramus) is generally identified and treated with a “keep it open” approach. Favorable early and long-term results have been reported, even in true trifurcation lesions that are at high risk for restenosis (97,98).

ISOLATED OSTIAL LAD OR LCX (MEDINA 0,0,1)

For ostial LAD, a single crossover into the LM as in PS followed by the POT is recommended. For ostial LCx, a 2-stent strategy demonstrated lower TLR (3.2% vs. 12.0%, $p = 0.07$) and TLF (4.8% vs. 12.0%, $p = 0.16$) than the 1-stent strategy (99,100).

HYBRID CORONARY REVASCULARIZATION

A feasibility study was reported of 22 patients with LM stenosis who underwent minimally invasive robotic left internal mammary artery-to-LAD bypass followed by PCI with stenting from the LM to the LCx. No MAEs were reported at 30 days or 3 years (101).

BIOABSORBABLE SCAFFOLDS IN LMB INTERVENTIONS

There are limitations to the broad application of bioabsorbable scaffolds in LMB interventions. LM diameters are often larger than 4.0 mm, and only a small proportion of patients may be suitable for the Absorb bioresorbable vascular scaffold (Abbott Vascular, Santa Clara, California) or the DESolve stent (Elixir Medical, Sunnyvale, California), with restricted expansion limits of 4.0 and 4.5 mm, respectively. Placing undersized stents in the LM increases the risk for stent malposition and underexpansion, which might increase the risk for stent thrombosis (102). Moreover, the recommended gradual slow inflation of the Absorb stent (60 s) could induce myocardial ischemia and hypotension during LM interventions. Finally, given the strut thickness of the Absorb bioresorbable vascular scaffold, 2-stent techniques may increase the risk for scaffold thrombosis, and on the basis of current data, LMB intervention is investigational and cannot be recommended (103,104).

CONCLUSIONS

LMB interventions using second-generation DES are safe, with clinical outcomes comparable with those obtained with CABG. However, late TLR is a concern. A single-stent provisional approach is the preferred strategy. Case selection, careful pre-procedure planning, knowledge of current techniques, and post-procedure intracoronary imaging will improve patient outcomes.

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KEY WORDS bifurcation, left main, stenting techniques

APPENDIX For supplemental tables, please see the online version of this article.