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Functional and Morphological Assessment of Side Branch after Left Main Coronary Artery Bifurcation Stenting with Cross-Over Technique

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Background: In left main coronary artery (LMCA) bifurcation lesions, hemodynamic and geometrical change in left circumflex artery (LCX) ostium after main branch (MB) stenting has not been known. This study evaluated how accurately intravascular ultrasound (IVUS) predicts the functional compromise of the sidebranch. Methods: A single-stent cross-over technique was used to treat LMCA bifurcation lesions in 43 patients with LCX ostial diameter stenosis (DS) of <50%. The fractional flow reserve (FFR) in the LCX was measured after MB stenting, MB and sidebranch pullback IVUS was performed prestenting and poststenting. Results: After MB stenting, angiographic DS >50% at the LCX ostium was observed in 18 (42%) patients, while only 3 (7%) showed FFR <0.80. A pre-procedural minimal lumen area (MLA) of <3.7 mm^2 within the LCX ostium was predictive of a poststenting FFR <0.80, with a sensitivity of 100%, specificity of 71%, a positive predictive value (PPV) of 16%, and a negative predictive value (NPV) of 100% (area under curve 0.80, $P < 0.001$). Moreover, pre-procedural plaque burden of >56% at the LCX ostium predicted FFR <0.80, with a sensitivity of 100%, specificity of 65%, a PPV of 14%, and a NPV of 100% (area under curve 0.80, $P < 0.001$). A poststenting LCX ostial DS >57% predicted FFR <0.80 with a sensitivity of 100%, specificity of 88%, a PPV of 38% and a NPV of 100% (area under curve 0.962, $P < 0.001$). However, the poststenting MLA within the LCX ostium showed no significant correlation with FFR ($r = 0.197$, $P = 0.391$). Conclusions: In LMCA bifurcation lesions with mild LCX ostial disease, the use of single-stent technique rarely resulted in the functional LCX compromise. Because the functional LCX stenosis is poorly predicted by a small MLA, sidebranch treatment should be based on the poststenting FFR.

Key words: fractional flow reserve; sidebranch; left main coronary artery stenosis

INTRODUCTION

In terms of clinical outcome, a single-stent strategy is superior to a two-stent strategy for treating left main coronary artery (LMCA) bifurcation lesions. However, there are remaining concerns about the high risk for sidebranch (SB) compromise [1–5]. Even though intravascular ultrasound (IVUS) provides more accurate information about disease involving the SB ostium than angiography [5–8], the use of IVUS to guide the initial stenting strategy is limited by the lack of IVUS criteria describing "significant SB disease," which is likely to lead to functional compromise following main branch (MB) stenting. Angiographic jailing of the SB ostium frequently occurs as a result of carina or plaque shift [9–12]. Previous data suggest that treatment of the SB lesion should be based on functional significance [13]. Although large discrepancies between the degree of anatomical stenosis and the physiological

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significance of SB ostial lesions have been noted in non-LMCA bifurcation lesions, there are a few data pertaining to LMCA bifurcations [13,14]. Thus, the present study had two main aims: first, to assess the ability of pre-procedural IVUS to predict functional compromise of the left circumflex artery (LCX) ostium and, second, to assess differences in visual–functional mismatch of LCX ostial stenosis after MB stenting using quantitative coronary angiography, IVUS, and fractional flow reserve (FFR).

METHODS

Subjects

Between June 2009 and December 2011, 116 patients with significant LMCA bifurcation disease (angiographic diameter stenosis [DS] >50%) and mild ostial disease of the LCX (DS ≤ 50%) underwent single-stent cross-over. Immediately after MB stenting, the FFR in the LCX was measured in patients who showed a poststenting LCX ostial DS of >20%. Thirty (26%) patients with normal-looking LCX ostium (poststenting LCX ostial DS <20%) and one (1%) patient with a total occlusion of the SB ostium were excluded. In addition, the patients who had serious comorbid disease, ejection fraction <40%, the presence of regional wall motion abnormalities on echocardiography, in-stent restenosis, ST-elevation myocardial infarction requiring primary percutaneous coronary intervention, and history of coronary artery bypass surgery were also excluded. The lesion exclusion criteria were significant distal stream disease (DS of secondary stenosis >50%), diffuse severe LCX disease extending from the ostium (>5 mm), a small LCX (distal reference lumen diameter ≤2.25 mm), visible thrombi on coronary angiography, and culprit lesion of acute myocardial infarction. Forty-eight patients were eligible to progress to FFR measurement; however, five (10%) patients experienced wire passage failure because of tight stenosis or tortuosity. Thus, a total of 43 lesions in 43 patients were available for definitive analysis. The ability to undergo both MB- and SB-pullback IVUS imaging pre- and poststenting was assessed. Preprocedural LCX-pullback IVUS was possible in 37 patients. Poststenting LCX-pullback IVUS was possible in 21 patients. Jailed SB lesions after MB stenting were treated using a final kissing balloon or a provisional T stent at the operators' discretion.

Major adverse cardiac events (MACE) at 1 year were defined as death, target lesion revascularization (TLR), and myocardial infarction. Revascularization was defined as "ischemia-driven" if there was angiographic DS of ≥50%, as documented by a positive functional study, ischemic changes on an electrocardiogram, or ischemic symptoms. In addition, lesions with an angiographic DS of ≥70%, as assessed by quantitative coronary analysis, were considered to be "ischemia-driven" even in the absence of documented ischemia. Myocardial infarction was diagnosed by the presence of ischemic symptoms or signs, as well as elevated cardiac enzyme levels (creatine kinase-myocardial band elevation >3 times, or creatine kinase elevation >2 times the upper limit of normal, or a troponin I level of >1.5 ng/ml). Written informed consent was obtained from all patients before proceeding.

Angiographic Analysis

Qualitative and quantitative angiographic analyses were performed at the angiographic analysis centre at the Cardiovascular Research Foundation, Seoul, Republic of Korea using standard techniques and automated edge-detection algorithms (CAAS-5, Pie-Medical, the Netherlands) [15,16]. The Medina classification was used to describe the location and distribution of lesions at the bifurcation [16].

IVUS Imaging and Analysis

IVUS imaging was performed after intracoronary administration of 0.2 mg nitroglycerin using motorized transducer pullback (0.5 mm/s) and a commercial scanner (Boston Scientific/SCIMED, Minneapolis, MN) consisting of a rotating 40 MHz transducer within a 3.2Fr imaging sheath. Using computerized planimetry (EchoPlaque 3.0, Indec Systems, MountainView, CA), off-line IVUS analysis was performed in the IVUS core laboratory of Asan Medical Center (Seoul, Republic of Korea).

Pre-intervention four segments of the bifurcation were assessed using both MB-pullback and SB-pullback before any balloon inflation. The carina was identified as the frame immediately distal to the take-off of the side branch [17]. From the MB-pullback the following were identified: MB ostium (3 mm distal to the carina), polygon of confluence (POC, confluence zone of MB and SB on longitudinal IVUS image reconstruction in parallel with the angiographic definition suggested by Ramcharitar and modified for IVUS analysis), and MB just proximal to the polygon of confluence [5,8,12,18]. Separately using the SB pullback, the ostium of the SB (3 mm distal to the carina) was defined. At the minimal lumen area (MLA) site within each of these four segments, the lumen, stent, plaque plus media, and external elastic membrane (EEM) areas were measured by 2D-planimetry. Plaque burden was calculated as plaque plus media/EEM × 100 (%).

In the single-stent group, poststenting LCX-pullback IVUS was performed immediately after stent implantation of the MB and before any SB balloon inflations. In addition, stented segments of MB were assessed by final IVUS. In the two-stent group, the four segments were assessed by final IVUS imaging, in parallel with the preprocedural IVUS analysis. Both the minimal stent area within each segment and the stent, lumen, and EEM areas at the SB ostium and carina were measured.

FFR Measurement

The FFR in the LCX was measured after drug-eluting stent implantation of the MB using the cross-over technique and before any SB balloon inflations. "Equalization" of the two pressures was performed with the guide wire sensor positioned at the guiding catheter tip. Next, the 0.014-in pressure guide wire (St. Jude Medical, Minneapolis, MN) was passed through the MB stent struts into the distal LCX. The FFR was then measured distal to the LCX ostial lesions under conditions of maximal hyperemia, which were induced by intravenous adenosine infusion (140–240 μg/kg/min) through a central vein. Hyperaemic pressure pullback recordings were performed as previously described [19,20]. LCX stenosis was considered functionally significant when the poststent FFR was <0.80. Hyperaemic pressure pullback recordings were performed as described previously [10,11,17]. LCX stenosis was considered functionally significant when the poststent FFR was <0.80.

Statistical Analysis

All statistical analyses were performed using SPSS (version 10.0, SPSS Inc., Chicago, IL). All values are expressed as the mean ± standard deviation (continuous variables) or as counts and percentages (categorical variables). Continuous variables were presented as mean ± SD or median (inter-quartile range [IQR]) and compared using unpaired or paired Student *t*-test. Categorical variables were compared with the χ^2 statistics or Fisher's exact test. Receiver-operating curve were analyzed to assess the best cut-off values of IVUS parameters to determine poststenting LCX FFR <0.80, using MedCalc (MedCalc Software, Mariakerke, Belgium). The optimal cutoff was calculated using the Youden index. The sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) with 95% confidence intervals were obtained. A P value <0.05 was considered statistically significant.

TABLE I. Baseline Clinical and Procedural Characteristics in 43 Patients

Age (Yr)	62 ± 9
Men	32 (75%)
Smoker	28 (65%)
Hypertension	28 (65%)
Hyperlipidemia[a]	34 (79%)
Diabetes mellitus	16 (37%)
Ejection fraction (%)	58 ± 7
Previous percutaneous coronary intervention	6 (14%)
Previous myocardial infarction	1 (2%)
Renal failure	0 (0%)
Clinical presentation	
Stable angina pectoris	33 (77%)
Unstable angina pectoris	10 (23%)
Drug-eluting stent type	
Cypher, *N* (%)	4 (9%)
Xience, *N* (%)	14 (33%)
Promus element, *N* (%)	15 (35%)
Nobori	3 (7%)
Other drug-eluting-stents, *N* (%)	7 (16%)

[a]Defined as total cholesterol >200 mg/dl, or receiving anti-lipidemic treatment

RESULTS

Clinical Characteristics and Angiographic Findings

The baseline clinical and procedural characteristics in the 43 patients are summarized in Table I. Medina classification was (1,1,0) in 21 (48%) patients, (0,1,0) in 14 (33%) patients, and (1,0,0) in 8 (19%) patients. All patients showed a preprocedural angiographic DS of ≤50% within the LCX ostium. After MB stenting, 18 (42%) patients showed an LCX ostial DS of >50%. The pre- and poststenting LCX ostial DSs were 23.4% (IQR 15.3–36.0%) and 39.8% (IQR 32.8–55.9%), respectively. The quantitative coronary angiographic data is shown in Table II.

IVUS Data

The pre- and poststenting IVUS data are summarized in Table III. The pre- and poststenting MLAs were 5.4 mm^2 (IQR 3.6–6.8 mm^2) and 4.7 mm^2 (IQR 3.5–5.2 mm^2), respectively. Preprocedure, there was a significant correlation between angiographic DS and MLA within the LCX ostium ($r=-0.583$, $P<0.001$). However, there was no correlation between angiographic DS and MLA after MB stenting ($r=-0.225$, $P=0.327$).

Angiographic and IVUS Predictors for FFR

The poststenting FFR was related to the preprocedural angiographic DS of the LCX ostium ($r=-0.354$, $P=0.020$), the preprocedural MLD of the LCX ostium ($r=0.417$, $P=0.020$), the poststenting

TABLE II. Quantitative Coronary Angiographic Data in 43 Patients

	Preprocedure	After MB stenting
Angiographic data	43	43
Minimal lumen diameter within LMCA (mm)	1.6 ± 0.6	3.5 ± 0.4
Percent diameter stenosis of LMCA	55.5 ± 16.6	3.6 ± 9.3
Minimal lumen diameter within left anterior descending artery ostium (mm)	1.5 ± 0.7	2.9 ± 0.4
Percent diameter stenosis of left anterior descending artery ostium	56.1 ± 21.7	5.0 ± 9.6
Minimal lumen diameter within polygon of confluence (mm)	1.8 ± 0.6	3.5 ± 0.4
Percent diameter stenosis of polygon of confluence	49.2 ± 17.3	3.5 ± 9.4
Minimal lumen diameter within LCX ostium (mm)	2.4 ± 0.4	1.9 ± 0.6
Percent diameter stenosis of LCX ostium	25.3 ± 11.7	43.8 ± 13.8
Distal bifurcation angle (°)	98.6 ± 29.4	92.3 ± 29.1
Proximal bifurcation angle (°)	100.1 ± 29.8	98.0 ± 25.2
TIMI 3 at the LCX, *N* (%)	43 (100%)	40 (100%)
TIMI 3 at the left anterior descending artery, *N* (%)	42 (98%)	40 (100%)

LCX, left circumflex artery; LMCA, left main coronary artery.

TABLE III. Pre- and PostStenting IVUS Data

	Preprocedure	After MB stenting
Main branch IVUS data, *N*	**38**	**35**
At the left anterior descending artery ostium		
MLA within the left anterior descending artery ostium (mm^2)	4.0 ± 1.8	8.9 ± 1.5
Vessel area at the MLA site (mm^2)	13.8 ± 3.0	17.3 ± 3.0
MLA within the polygon of confluence (mm^2)	5.1 ± 2.5	10.1 ± 1.6
At the proximal LMCA		
MLA within the LMCA (mm^2)	5.8 ± 3.1	10.5 ± 1.5
Vessel area at the MLA site (mm^2)	19.1 ± 5.2	23.1 ± 5.1
Sidebranch IVUS data, *N*	**37**	**21**
MLA within the LCX ostium (mm^2)	5.4 ± 2.1	4.6 ± 2.1
Vessel area at the MLA site (mm^2)	11.6 ± 4.3	11.2 ± 4.3
Plaque burden at the MLA site (%)	51.9 ± 13.0	59.7 ± 14.5
Lumen area at the LCX ostium carina (mm^2)	6.2 ± 2.8	5.0 ± 2.3
Vessel area at the LCX ostium carina (mm^2)	12.4 ± 4.3	12.1 ± 4.6
Plaque burden at the LCX ostium carina (%)	49.2 ± 13.1	58.3 ± 14.6
Vessel eccentricity index	1.0 ± 0.1	0.9 ± 0.2

IVUS, intravascular ultrasound; LCX, left circumflex artery; LMCA, left main coronary artery; MLA, minimal lumen area.

DS of the LCX ostium ($r = -0.455$, $P = 0.002$), and the poststenting MLD of the LCX ostium ($r = 0.480$, $P = 0.001$; Fig. 1). Conversely, the preprocedural distal bifurcation angle showed no correlation with the poststenting FFR ($r = 0.104$, $P = 0.509$). Among the 18 patients with a poststenting LCX ostial DS of >50%, 15 (83%) showed an FFR of ≥0.80. A poststenting LCX ostial DS of >57% predicted an FFR of <0.80, with a sensitivity of 100%, specificity of 88%, a PPV of 38%, and an NPV of 100% (area under curve [AUC] = 0.962, 95% CI 0.855–0.955, $P < 0.001$).

At the LCX ostium, the preprocedural MLA was 5.4 ± 2.1 mm^2 and plaque burden was 51.9 ± 13.0%. The pre-procedural plaque burden within the LCX ostium moderately correlated with the poststenting FFR ($r = -0.395$, $P = 0.015$), while no significant relationship between preprocedural MLA within the LCX ostium and the FFR was found ($r = 0.312$, $P = 0.060$; Fig. 2). Although the MLA within the LCX ostium varied from 2.3 mm^2 to 11.8 mm^2, only 2 (5%) patients had an FFR of <0.80. A preprocedural MLA within the LCX ostium of <3.7 mm^2 predicted a poststenting FFR of <0.80, with a sensitivity of 100%, specificity of 71%, a PPV of 16%, and an NPV of 100% (AUC = 0.80, 95% CI 0.636–0.913, $P < 0.001$; Fig. 3). Moreover, a preprocedural plaque burden at the LCX ostium of >56% predicted a poststenting FFR of <0.80, with a sensitivity of 100%, specificity of 65%, a PPV of 14%, and an NPV of 100% (AUC = 0.80, 95% CI 0.630–0.920, $P < 0.001$).

The poststenting MLA within the LCX ostium was 4.6 ± 2.1 mm^2 and the plaque burden was 59.7 ± 14.5%. The plaque burden within the LCX ostium correlated with the poststenting FFR ($r = -0.452$, $P = 0.040$), whereas there was no significant correlation between the MLA within the LCX ostium and the FFR ($r = 0.197$, $P = 0.391$; Fig. 2). The range of the poststenting MLA within the LCX ostium was 1.8–11.2 mm^2. Although there were nine patients showing an MLA within the LCX ostium of <4.0 mm^2 and 17 patients with a plaque burden at the LCX ostium of >50%, an FFR of <0.80 was seen in only one patient.

Follow-up Clinical Outcomes

LCX ostial stenosis was treated using a final kissing balloon in 4 (10%) of 40 patients with an FFR of ≥0.80 and 2 (67%) of 3 patients with an FFR of <0.80. Over a median follow-up period of 12.5 months (inter-quartile range 8.8–24.7 months), 1-year MACE occurred in 2 (5%) patients. There was no TLR or myocardial infarction. Of the 37 patients with deferred LCX lesions (not treated with a kissing balloon or a provisional stent), one elderly patient (an 85-year-old male) died from unknown cause. Of the six patients treated with the final kissing balloon, one patient (an 83-year-old male) died of unknown causes.

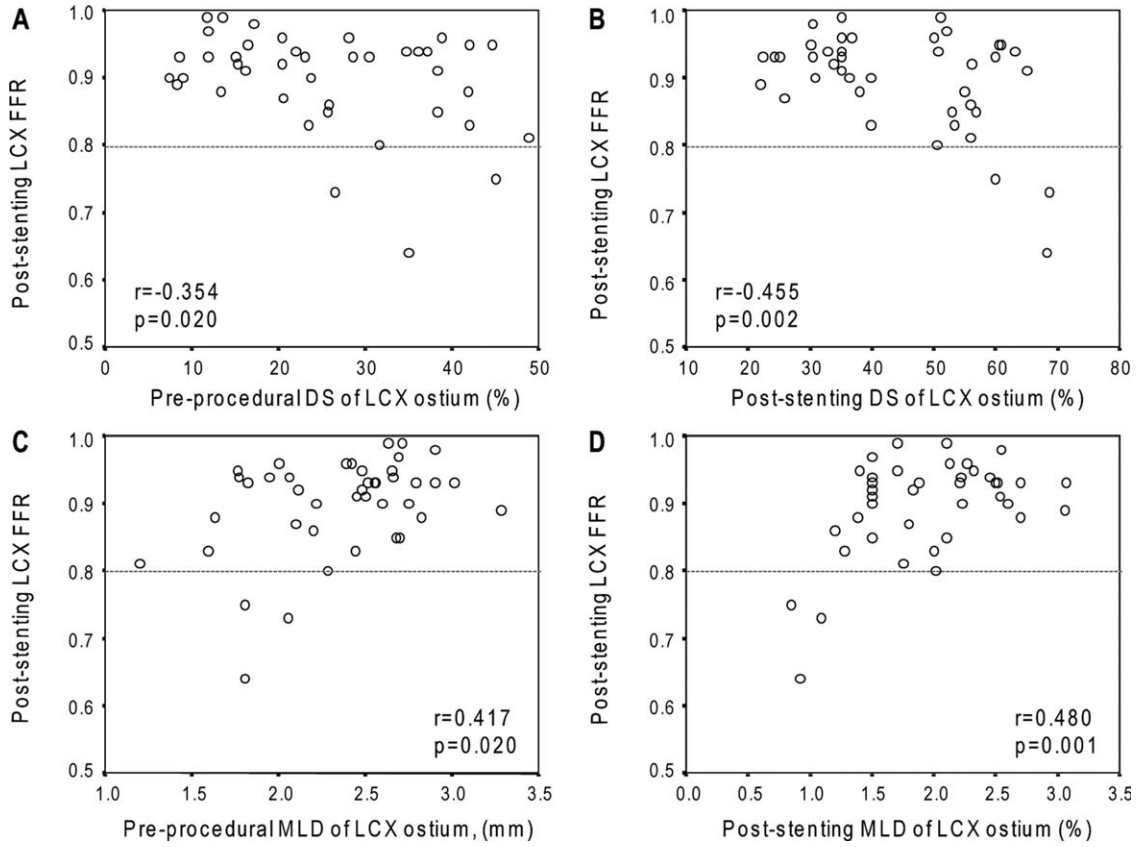

Fig. 1. Correlation between pre- and poststenting angiographic parameters and poststenting FFR in the LCX. DS, diameter stenosis; FFR, fractional flow reserve; LCX, left circumflex coronary artery; MLD, minimal lumen diameter.

DISCUSSION

There were two key findings from our study: first, functional compromise of the LCX ostium after MB stenting occurred in only 7% of LMCA bifurcation lesions with a preprocedural LCX ostial DS of $\leq$50%; second, neither angiographic DS nor IVUS–MLA could accurately predict functional LCX compromise with an FFR of $<$0.80. It is reported that angiographic DS and IVUS–MLA usually overestimate the functional severity of SB stenosis in non-LMCA bifurcation lesions [13,14,20]. In our patients with normal looking preprocedure LCX ostia, 42% showed angiographic jailing of the LCX ostium (DS $>$ 50%), while a poststenting FFR of $<$0.80 was observed in only 7%. Therefore, our findings in LMCA bifurcation lesions are similar to previous findings in non-LMCA bifurcations in that functional stenosis is less common than anatomical stenosis at the LCX ostium [13,14,20]. The use of a single-stent cross-over technique resulted in good SB flow in the majority of patients with preprocedural minimal LCX ostial disease (DS $<$ 50%).

Poststenting DS of the LCX ostium showed no correlation with the IVUS–MLA and poorly predicted an FFR of $<$0.80, suggesting that the angiographic severity of the stenosis was inaccurate both morphologically and functionally. The discordance between angiographic DS and IVUS–MLA may be explained by lesion eccentricity of the LCX ostium and stent strut artefacts [11,12]. Furthermore, our study demonstrated that a small IVUS–MLA within the LCX ostium did not always represent a functionally significant stenosis. A previous IVUS study demonstrated that the majority of LMCA bifurcation lesions showed a geometrical change after cross-over MB stenting related to carina shift, which was characterized by a reduction in the vessel and lumen area of the LCX ostium and a more eccentric vessel shape [12]. Because carina shift is very focal change and myocardial territory of SB is relatively small, functional compromise of the LCX ostium may rarely, if ever, occur [11,13,14,19]. For the treatment of SB stenosis, angiographic- or IVUS-based decision making may frequently lead to unnecessary procedures. Thus, functional assessment with poststenting FFR is needed to determine how to treat the angiographically jailed SB.

One-year MACE occurred in only 1 (3%) of 37 patients with a deferred LCX lesion. No patient

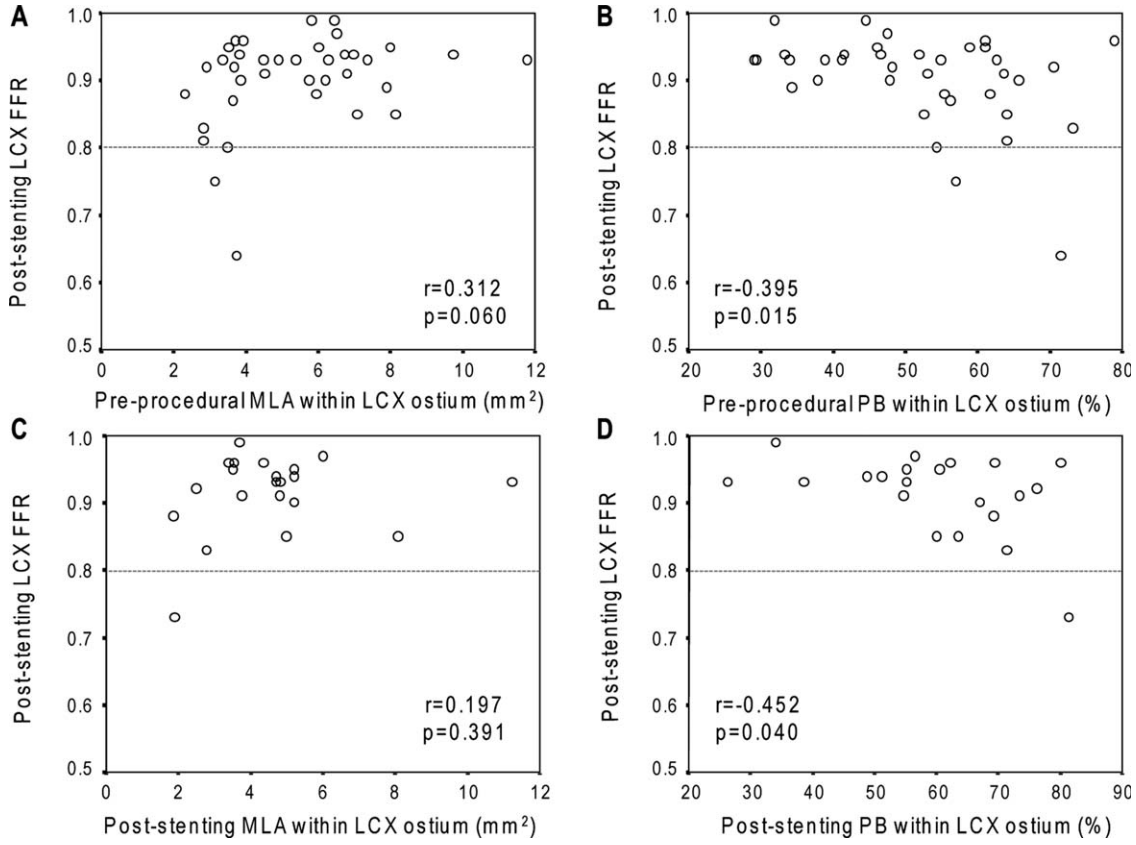

Fig. 2. Correlation between prestenting and poststenting IVUS parameters and poststenting FFR in the LCX. FFR, fractional flow reserve; IUVS, intravascular ultrasound coronary artery; LCX, left circumflex coronary artery; MLA, minimal lumen area; PB, plaque burden.

experienced repeat revascularisation or myocardial infarction. The current observation suggests that FFR-guided deferral of the jailed SB with normal FFR may be safe in LMCA bifurcations as well as non-LMCA bifurcations [13].

From a practical point of view, identification of preprocedural IVUS predictors for functional SB compromise is important in order to select the use of the single- or two-stent technique. In this study, the preprocedural plaque burden at the LCX ostium correlated with the poststenting FFR, which supports our view of determining the initial stent strategy based on the disease status of the LCX ostium. A preprocedural MLA within the LCX ostium of ≥ 3.7 mm^2 or a plaque burden of $<56\%$ excluded the possibility of functional LCX compromise (NPV = 100%). Conversely, when MLA was <3.7 mm^2, or the plaque burden was $\geq 56\%$, there was only a small probability of predicting an FFR of <0.80 (PPV = 15%). These findings are consistent with our previous study, which evaluated nonLMCA bifurcations. A preprocedural MLA within the SB ostium <2.4 mm^2 predicted a poststenting SB FFR of <0.80, (PPV = 40% and NPV = 98%) in non-LMCA bifurcation lesions. Even in the LCX ostium with a small MLA, functional significance should be confirmed by verifying that the poststenting FFR is <0.80.

In a previous study, a narrow distal carina angle was related to a large carina shift and a greater loss in lumen and vessel area at the LCX ostium [12]. However, the current data show no correlation between the distal carina angle and poststenting LCX FFR. Therefore, the hemodynamic impact of the carina angle on the poststenting LCX flow appears to be minor.

Limitations

The sample size was relatively small and the single-stent group included selected patients with a preprocedure LCX ostial DS of $<50\%$. As a result, the small number of functional SB compromise limited to identify the optimal IVUS criteria predicting FFR. Nevertheless, our results indicate that the use of the single-stent technique in LMCA bifurcation lesions with mild LCX ostial stenosis was generally effective in maintaining SB patency. Furthermore, deferral of the LCX

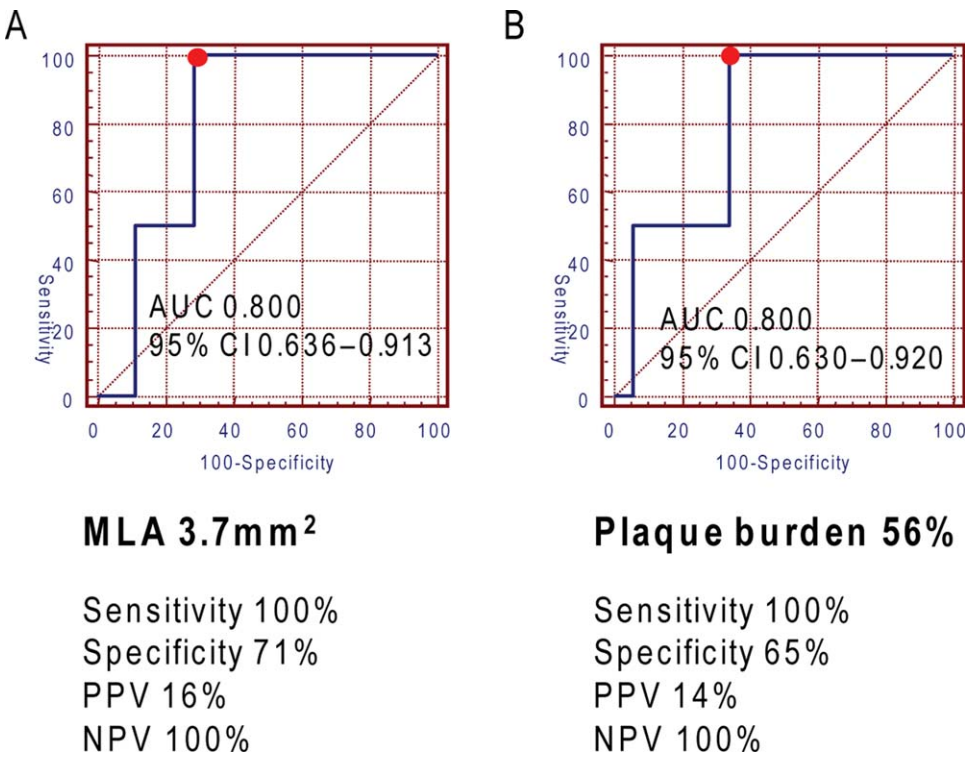

Fig. 3. (A) Preprocedural MLA within the LCX ostium predicting a poststenting FFR of <0.80. (B) Preprocedural plaque burden at the LCX ostium predicting a poststenting FFR of <0.80. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

lesions with a normal FFR resulted in a low 1-year MACE rate. A further limitation was that IVUS could not be performed in all cases because of technical difficulties associated with SB-pullback. This reflects the limitation of the use of this technology in normal clinical practice. A final limitation is that, although an FFR of 0.75 has been confirmed as safe for the deferral of SB lesions of non-LMCA bifurcations, there is no validated FFR cut-off (either 0.75 or 0.80) for LMCA bifurcation lesions. Further study is needed to clarify this issue.

CONCLUSIONS

In LMCA bifurcation lesions with mild LCX ostial disease, the use of the single-stent technique was not associated with functional LCX compromise or adverse cardiac events. The functional significance of LCX ostial stenosis was poorly predicted by either a high degree of DS on angiography, or a small IVUS–MLA following MB stenting.

REFERENCES

1. Colombo A, Bramucci E, Saccà S, Violini R, Lettieri C, Zanini R, Sheiban I, Paloscia L, Grube E, Schofer J, Bolognese L, Orlandi M, Niccoli G, Latib A, Airoldi F. Randomized study of the crush technique versus provisional side-branch stenting in true coronary bifurcations: The CACTUS (Coronary bifurcations: Application of the crushing technique using sirolimus-eluting stents) study. Circulation 2009;119:71–78.
2. Steigen TK, Maeng M, Wiseth R, Erglis A, Kumsars I, Narbute I, Gunnes P, Mannsverk J, Meyerdierks O, Rotevatn S, Niemelä M, Kervinen K, Jensen JS, Galløe A, Nikus K, Vikman S, Ravkilde J, James S, Aarøe J, Ylitalo A, Helqvist S, Sjögren I, Thayssen P, Virtanen K, Puhakka M, Airaksinen J, Lassen JF, Thuesen L; Nordic PCI Study Group. Randomized study on simple versus complex stenting of coronary artery bifurcation lesions: The Nordic Bifurcation Study. Circulation 2006;114: 1955–1961.
3. Ferenc M, Gick M, Kienzle RP, Bestehorn HP, Werner KD, Comberg T, Kuebler P, Büttner HJ, Neumann FJ. Randomized trial on routine vs provisional T-stenting in the treatment of de novo coronary bifurcation lesions. Eur Heart J 2008;29:2859–2867.
4. Colombo A, Moses JW, Morice MC, Ludwig J, Holmes DR Jr, Spanos V, Louvard Y, Desmedt B, Di Mario C, Leon MB. Randomized study to evaluate sirolimus-eluting stents implanted at coronary bifurcation lesions. Circulation 2004;109:1244–1249.
5. Kim WJ, Kim YH, Park DW, Yun SC, Lee JY, Kang SJ, Lee SW, Lee CW, Park SW, Park SJ. Comparison of single- versus two-stent techniques in treatment of unprotected left main coronary bifurcation disease. Catheter Cardiovasc Interv 2011;77: 775–782.
6. Kang SJ, Mintz GS, Kim WJ, Lee JY, Park DW, Yun SC, Lee SW, Kim YH, Lee CW, Han KH, Kim JJ, Park SW, Park SJ. Impact of intravascular ultrasound findings on the long-term

repeat revascularization in patients undergoing drug eluting stent implantation for severe unprotected left main bifurcation narrowing. Am J Cardiol 2011;107:367–373.
7. Oviedo C, Maehara A, Mintz GS, Tsujita K, Kubo T, Doi H, Castellanos C, Lansky AJ, Mehran R, Dangas G, Leon MB, Stone GW, Templin B, Araki H, Ochiai M, Moses JW. Is accurate intravascular ultrasound evaluation of the left circumflex ostium from a left anterior descending to left main pullback possible? Am J Cardiol 2010;105:948–954.
8. Kang SJ, Mintz GS, Oh JH, Park DW, Lee SW, Kim YH, Lee CW, Park SW, Park SJ. Intravascular ultrasound assessment of distal left main bifurcation disease: The importance of the polygon of confluence of the left main, left anterior descending, and left circumflex arteries. Catheter Cardiovasc Interv 2013;82: 737–745.
9. Vassilev D, Gil R. Clinical verification of a theory for predicting side branch stenosis after main vessel stenting in coronary bifurcation lesions. J Interv Cardiol 2008;21:493–503.
10. Gil RJ, Vassilev D, Formuszewicz R, Rusicka-Piekarz T, Doganov A. The carina angle-new geometrical parameter associated with periprocedural side branch compromise and the long-term results in coronary bifurcation lesions with main vessel stenting only. J Interv Cardiol 2009;22:E1–E10.
11. Koo BK, Waseda K, Kang HJ, Kim HS, Nam CW, Hur SH, Kim JS, Choi D, Jang Y, Hahn JY, Gwon HC, Yoon MH, Tahk SJ, Chung WY, Cho YS, Choi DJ, Hasegawa T, Kataoka T, Oh SJ, Honda Y, Fitzgerald PJ, Fearon WF. Anatomic and functional evaluation of bifurcation lesions undergoing percutaneous coronary intervention. Circ Cardiovasc Interv 2010;3:113–119.
12. Kang SJ, Mintz GS, Kim WJ, Lee JY, Oh JH, Park DW, Lee SW, Kim YH, Lee CW, Park SW, Park SJ. Changes in left main bifurcation geometry after a single-stent crossover technique: An intravascular ultrasound study using direct imaging of both the left anterior descending and the left circumflex coronary arteries before and after intervention. Circ Cardiovasc Interv 2011;4:355–361.
13. Koo BK, Park KW, Kang HJ, Cho YS, Chung WY, Youn TJ, Chae IH, Choi DJ, Tahk SJ, Oh BH, Park YB, Kim HS. Physiological evaluation of the provisional side-branch intervention strategy for bifurcation lesions using fractional flow reserve. Eur Heart J 2008;29:726–732.
14. Kang SJ, Mintz GS, Kim WJ, Lee JY, Park DW, Lee SW, Kim YH, Lee CW, Park SW, Park SJ. Preintervention angiographic and intravascular ultrasound predictors for side branch compromise after a single-stent crossover technique. Am J Cardiol 2011;107:1787–1793.
15. Ryan TJ, Faxon DP, Gunnar RM, Kennedy JW, King SB III, Loop FD, Peterson KL, Reeves TJ, Williams DO, Winters WL Jr. Guidelines for percutaneous transluminal coronary angioplasty. A report of the American College of Cardiology/American Heart Association Task Force on Assessment of Diagnostic and Therapeutic Cardiovascular Procedures (Subcommittee on Percutaneous Transluminal Coronary Angioplasty). Circulation 1988;78:486–502.
16. Medina A, Suárez de Lezo J, Pan M. A new classification of coronary bifurcation lesions. Rev Esp Cardiol 2006;59:183.
17. Rodriguez-Granillo GA, García-García HM, Wentzel J, Valgimigli M, Tsuchida K, van der Giessen W, de Jaegere P, Regar E, de Feyter PJ, Serruys PW. Plaque composition and its relationship with acknowledged shear stress patterns in coronary arteries. J Am Coll Cardiol 2006;47:884–885.
18. Ramcharitar S, Onuma Y, Aben JP, Consten C, Weijers B, Morel MA, Serruys PW. A novel dedicated quantitative coronary analysis methodology for bifurcation lesions. EuroIntervention 2008;3:553–557.
19. Pijls NH, De Bruyne B, Peels K, Van Der Voort PH, Bonnier HJ, Bartunek J Koolen JJ, Koolen JJ. Measurement of fractional flow reserve to assess the functional severity of coronary artery stenoses. N Engl J Med 1996;334:1703–1708.
20. Koo BK, Kang HJ, Young TJ, Chae IH, Choi DJ, Kim HS, Sohn DW, Oh BH, Lee MM, Park YB, Choi YS, Tahk SJ. Physiologic assessment of jailed side branch lesions using fractional flow reserve. J Am Coll Cardiol 2005;46:633–637.