Physiology and Fluid Dynamics of Bifurcation Lesions

Bon-Kwon Koo, MD, PhD

Associate Professor, Seoul National University, Seoul, Korea
Evaluation of Bifurcation lesions

- Clinical information: Symptom, risk factors, ..... 
- Functional study: SPECT, TMT, ..... 
- Angiographic findings 
- Quantitative coronary angiography 
- Intravascular ultrasound 
- OCT, ..... 

Is there a room for more?
Pitfalls of anatomical evaluation

• Angiography
  - Single directional assessment
  - Variability in stenosis assessment
  - No validated criteria for side branch intervention

• IVUS/OCT
  - Can not be performed in tight stenosis
  - Does not reflect the amount of supplying myocardium
  - No validated criteria for side branch intervention
PCI for bifurcation lesions should be successful in terms of ....
PCI for bifurcation lesions should be successful in terms of ....

- Natural Anatomy
- Physiology
- Fluid dynamics
Physiologic evaluation assess the quantity of FLOW.

Fluid dynamics assess the quality of FLOW.
I love “Images”, **But, I hate “Physiology”!**

\[
\frac{Q_{c}}{Q_{c}^{0}} = \frac{Q_{c}^{0}}{Q_{c}^{0} - Q_{c}} = \frac{Q_{c}^{0} - P_{c}^{0} / (R_{c} - \Delta P_{c}^{0}) / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]

Equation (4) can also be derived directly from Figure 4.7 by the following:

\[
\frac{Q_{c}}{Q_{c}^{0}} = \frac{Q_{c}^{0} - P_{c}^{0} / (R_{c} - \Delta P_{c}^{0}) / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]

and by substituting Equation (3):

Theoretically, maximum blood flow through the coronary can be expressed before and after the intervention by:

\[
\frac{Q_{c}^{0}}{Q_{c}^{0}} = \frac{(P_{c}^{0} - P_{c}) / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]

or, if correction for pressure changes is made, by:

\[
\frac{\text{FFR}_{c}}{\text{FFR}_{c}^{0}} = \frac{P_{c}^{0} - P_{c}^{0} / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]

\[
\frac{Q_{c}}{Q_{c}^{0}} = \left(1 - \frac{\Delta P_{c}^{0}}{P_{c}^{0} - P_{c}^{0}} \right) \left(1 - \frac{\Delta P_{c}^{0}}{P_{c}^{0} - P_{c}^{0}} \right)
\]

In the case of coronary interventions, it should be evaluated that flow at maximum vasodilation is directly proportional to the driving pressure \(P_{c} - P_{c}^{0}\). Therefore, the ratio between maximum flow through the coronary artery before (situation 1) and after the intervention (situation 2) can be written as follows:

\[
\frac{Q_{c}}{Q_{c}^{0}} = \frac{Q_{c}^{0}}{Q_{c}^{0} - Q_{c}} = \frac{Q_{c}^{0} - P_{c}^{0} / (R_{c} - \Delta P_{c}^{0}) / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]

By substitution of Equations (1) and (3):

\[
\frac{Q_{c}}{Q_{c}^{0}} = \frac{P_{c}^{0} - P_{c}^{0} / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]

Note that for evaluation of the functional improvement of a stenotic artery after PTCA, \(\text{FFR}_{c}^{0} - \text{FFR}_{c}^{0}\) theoretically is a better measure than \(Q_{c}^{0} - Q_{c}^{0}\) because the first expression is independent of arterial pressure. From Equation 2 it is clear that:

\[
\frac{\text{FFR}_{c}}{\text{FFR}_{c}^{0}} = \frac{P_{c}^{0} - P_{c}^{0} / R_{c}}{P_{c}^{0} - P_{c}^{0} / R_{c}}
\]
A reliable parameter should account for the interaction between

- epicardial stenosis severity,
- extent of the perfusion territory,
- myocardial blood flow including collaterals
- microvascular function

Physiologic evaluation
Same stenosis, same functional significance?

LA: Lumen cross sectional area
Why “Physiologic evaluation” for bifurcation?

- Various amount of supplying myocardium
- Combination of 3 ostial lesions
- Jailed SB ostial lesion is unique
  - Underlying plaque → Eccentric plaque
  - Remodeling → Negative remodeling
  - Mechanisms of luminal narrowing
    - Shifted plaque
    - Shifted carina
    - Stent struts, thrombus, dissection flap,……

![Diagram showing bifurcation with various mechanisms of luminal narrowing]
What kind of physiologic parameter does really reflect the physiologic significance of a stenosis??

• Blood flow?

• Flow-derived parameters (such as CFR)?

• Transstenotic gradient itself or indexes of stenosis resistance?


**Fractional Flow Reserve (FFR)**

\[
FFR = \frac{Q^S_{\text{max}}}{Q^N_{\text{max}}} = \frac{(P_d - P_v)/R}{(P_a - P_v)/R} = \frac{P_d}{P_a}
\]

- Easily obtained, stenosis specific, simple (<0.75 or 0.8 \(\rightarrow\) ischemia)
- Reflects both degree of stenosis and myocardial territory

Pa: systemic pressure by guiding catheter
Pd: distal pressure by pressure wire

Significant Stenosis

| FFR | 1.0 | 0.80 | 0.75 | 0 |
Physiologic Assessment of Jailed Side Branch Lesions Using Fractional Flow Reserve

Bon-Kwon Koo, MD, PhD,* Hyun-Jae Kang, MD, PhD,‡ Tae-Jin Youn, MD, PhD,* In-Ho Chae, MD, PhD,‡ Dong-Joo Choi, MD, PhD,* Hye-Soo Kim, MD, PhD,* Dae-Won Sohn, MD, PhD,* Byung-Hee Oh, MD, PhD, FACC,* Myoung-Mook Lee, MD, PhD, FACC,* Young-Bae Park, MD, PhD,* Yu-Sik Choi, MD, PhD,* Seung-Jae Tahk, MD, PhD

Seoul, Seoulnam, Gyeonggi-do, and Suseon, Republic of Korea

OBJECTIVES

This study was performed to evaluate the feasibility of the physiologic assessment of jailed side branches using fractional flow reserve (FFR) and to compare the measured FFR with the stenosis severity assessed by quantitative coronary angiography (QCA).

BACKGROUND

It is not well-known which side branches should be treated after stent implantation and how to assess the functional significance of these lesions.

METHODS

Ninety-seven jailed side branch lesions (secured ≥ 2.0 mm, percent stenosis estimation) after stent implantation at main branches were consecutively assessed. After stenting, lesions were measured using a pressure wire at 5 mm distal and 20 mm proximal to the jailed side branch.

RESULTS

The FFR measurement was successful in 94 lesions. Mean FFRs were 0.94 ± 0.11 at the main branches and jailed side branches, respectively. There was no significant difference between the percent stenosis and FFR (r = 0.61; p < 0.01). However, stenosis had FFR < 0.75. Among 73 lesions with ≥ 50% stenosis, only 20 lesions had FFR ≥ 0.75.

CONCLUSIONS

The FFR measurement in jailed side branch lesions is both safe and feasible. Concomitantly, it is recommended for the assessment of the functional and non-functional lesions and measurement of FFR suggests that most of this lesion is not functionally significant. The Am Coll Cardiol 2005;46:635–7 © 2005 American Heart Association, Inc.

Anatomic and Functional Evaluation of Bifurcation Lesions Undergoing Percutaneous Coronary Intervention

Bon-Kwon Koo, MD, PhD, Karusihwa Wiseda, MD, PhD, Hyun-Jae Kang, MD, PhD, Hye-Soo Kim, MD, PhD, Chong-Wook Nam, MD, PhD, Seung-Ho Hur, MD, PhD, Jung-Sun Kim, MD, PhD, Donghoon Choi, MD, PhD, Yangsoo Jung, MD, PhD, Jong-Yong Han, MD, PhD, Heon-Seol Cwong, MD, PhD, Myoung-Ho Yoon, MD, PhD, Seung-Jae Tahk, MD, PhD, Woon-Yong Chung, MD, PhD, Young-Soo Cho, MD, PhD, Dong-Ju Choi, MD, PhD, Takao Hasegawa, MD, Toru Kataoka, MD, Sung Jin Oh, MD, Yasuhiro Honda, MD, Peter J. Fitzgerald, MD, PhD, William F. Fearon, MD

Background—We sought to investigate the mechanism of geometric changes after main branch (MB) stent implantation and to identify the predictors of functionally significant “jailed” side branch (SB) lesions.

Methods and Results—Seventy-two patients with bifurcation lesions were prospectively enrolled from 8 centers. MB intracoronary ultrasound was performed before and after MB stent implantation, and fractional flow reserve was measured in the jailed SB. The vessel volume index of both the proximal and distal MB was increased after stent implantation. The plaque volume index decreased in the proximal MB (9.3 ± 8.3 to 6.5 ± 4.7 mm³, p < 0.001), implying plaque shift, but not in the distal MB (5.0 ± 3.8 to 3.1 ± 3.6 mm³, p = 0.227), implying carina shifting to account for the change in vessel size (r = 0.54). The mean SB fractional flow reserve was 0.71 ± 0.20 ± 0.61 and 43% of the lesions were functionally significant. Binary logistic-regression analysis revealed that preintervention % diameter stenosis of the SB (odds ratio: 1.05; 95% CI, 1.01 to 1.09) and the MB minimum lumen diameter localized distal to the SB ostium (odds ratio: 3.98; 95% CI, 1.03 to 14.43) were independent predictors of functionally significant SB jailed. In patients with ≤ 75% stenoses and Thrombolysis In Myocardial Infarction grade 3 flow in the SB, no difference in postangiographic and intracoronary ultrasound parameters was found between SB lesions with and without functional significance.

Conclusions—Both plaque shift from the MB and carina shift contribute to the creation/leveling of an SB ostial lesion after MB stent implantation. Anatomic evaluation does not reliably predict the functional significance of a jailed SB stenosis.

Clinical Trial Registration: http://www.clinicaltrials.gov. Unique Identifier: NCT00556789

(Circ Cardiovasc Inter. 2010;3:113-119.)
Bifurcation lesion?
Should we measure FFR in these lesions?

Courtesy of Dr Colombo and Dr Airoldi
Is this the best we can achieve?

FFR > 0.8

Human cast model

OCT: 18 mo after Cypher

Deplano et al, Med Biol Eng Comput 2004
Low or abnormal wall shear stress

→ Proliferative, pro-inflammatory, pro-thrombotic stimulus
How can we assess local “flow conditions”?  
- Computational Fluid Dynamics -

• CFD quantifies fluid pressure and velocity, based on physical laws of mass conservation and momentum balance

• An ideal simulation tool for studying the local effects of blood flow

  • Requirements
    Model geometry and Computational mesh
    Inflow/Out flow boundary conditions
    Wall properties
**Stent cross over & Distal MB over-expansion**

MB Stent Implantation: Carina shift and distal MB over-expansion

Idealized Bifurcation Model

![Image](8x198 to 246x339)

Side Branch Angioplasty

Finet’s law
Fractal ratio \( \frac{\text{prx MB}}{\text{SB + dist MB}} \) = 0.678

Williams & Koo, J Appl Physiol 2010
Stent cross over & Distal MB over-expansion

MB Stent Implantation: Carina shift and distal MB over-expansion

Idealized Bifurcation Model

Side Branch Angioplasty

Finet's law
Fractal ratio \( \frac{\text{prx MB}}{\text{SB + dist MB}} \) = 0.678

Ostium Area = 1.94 mm²
Diameter stenosis = 54%
Area stenosis = 51%

Ostium Area = 3.89 mm²
Diameter stenosis = 0%
Area stenosis = 0%

Williams & Koo, J Appl Physiol 2010
Stent cross over & Distal MB over-expansion

Fractional flow reserve of Side branch

\[
\text{FFR} = \frac{Q_{max}^S}{Q_{max}^N} = \frac{P_d}{P_a}
\]

Post MB stenting

Side branch FFR

Post MB stenting  Post SB angioplasty
Stent cross over & Distal MB over-expansion

Time Averaged Wall Shear Stress

Normal bifurcation model

MB stenting

MB stenting + SB angioplasty

Wall Shear Stress (dyn/cm²)

Williams & Koo, J Appl Physiol 2010
Stent cross over & Distal MB over-expansion

Time Averaged Wall Shear Stress

Shear stress distribution

% area of low WSS (< 4dyne/cm²)

Post MB stenting
Post SB angioplasty

Williams & Koo, J Appl Physiol 2010
Additional side branch intervention?

MB and SB stenting → Aggressive kissing

SB stenting without kissing

MB stenting → Aggressive kissing

Reference segment
Average diameter: 3.7 mm
Eccentricity: 3.51/3.75 = 0.93

Proximal MB
Average diameter: 4.2 mm
Eccentricity: 3.6/5.0 = 0.71

Courtesy of Dr. Murasato

Koo, Nomeland and LaDisa
Distribution of Wall Shear Stress

Rest

MB/SB stenting without kissing

MB stenting with aggressive kissing

MB/SB stenting with aggressive kissing

Exercise

Koo, Nomeland and LaDisa
Distribution of wall shear stress

Koo, Nomeland and LaDisa
Wall Shear Stress Distribution along Axis

0 degree

180 degree

90 degree

270 degree

Proximal MB over-expansion
Clinical relevance of “abnormal flow”?

Limitations of current CFD analyses

- Simple models, not patient-specific
- Not completely reflects human coronary circulation
- No established clinical relevance
Patient-specific CFD analysis
Patient-specific CFD analysis
Summary

- Coronary bifurcation is complex.
- Physiologic evaluation is helpful to overcome the limitation of anatomical tools in bifurcation lesions.
- Evaluation of local flow dynamics using CFD can provide the local flow conditions in bifurcation lesions.
- Successful PCI for bifurcation lesions in terms of anatomy, physiology and flow dynamics may further improve the patients’ outcome.