Myocardial Bridging Contemporary Understanding of Pathophysiology With Implications for Diagnostic and Therapeutic Strategies

Michel T. Corban, Emory University
Olivia Y. Hung, Emory University
Parham Eshtehardi, Emory University
Emad Rasoul-Arzrumly, Emory University
Michael McDaniel, Emory University
Girum Mekonnen, Emory University
Lucas Timmins, Emory University
Jerre Lutz, Emory University
Robert Guyton, Emory University
Habib Samady, Emory University

Journal Title: Journal of the American College of Cardiology
Volume: Volume 63, Number 22
Publisher: Elsevier: 12 months | 2014-06-10, Pages 2346-2355
Type of Work: Article | Post-print: After Peer Review
Publisher DOI: 10.1016/j.jacc.2014.01.049
Permanent URL: https://pid.emory.edu/ark:/25593/v10rz

Final published version: http://dx.doi.org/10.1016/j.jacc.2014.01.049

Copyright information:
© 2014 by the American College of Cardiology Foundation Published by Elsevier Inc.
This is an Open Access work distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Accessed January 2, 2020 1:05 AM EST
Myocardial Bridging: Contemporary Understanding of Pathophysiology with Implications for Diagnostic and Therapeutic Strategies

Michel T. Corban, MD*, Olivia Y. Hung, MD, PhD#, Parham Eshtehardi, MD*, Emad Rasoul-Arzrumly, MD*, Michael McDaniel, MD*, Girum Mekonnen, MD, MPH†, Lucas H. Timmins, PhD†, Jerre Lutz, MD*, Robert A Guyton, MD‡, and Habib Samady, MD*

*Andreas Gruentzig Cardiovascular Center, Division of Cardiology, Department of Medicine, Emory University School of Medicine, Atlanta, GA
†Wallace H. Coulter Department of Biomedical Engineering, Georgia Institute of Technology and Emory University, Atlanta, GA
‡Division of Cardiothoracic Surgery, Department of Surgery, Emory University School of Medicine, Atlanta, GA

# These authors contributed equally to this work.

Abstract

Patients with myocardial bridges are often asymptomatic but this anomaly may be associated with exertional angina, acute coronary syndromes, cardiac arrhythmias, syncope or even sudden cardiac death. This review presents our understanding of the pathophysiology of myocardial bridging and describes prevailing diagnostic modalities and therapeutic options for this challenging clinical entity.

Keywords
Coronary Wall Shear Stress; Intravascular Imaging; Intracoronary Doppler Velocity and Pressure; Myocardial Bridge; Myotomy; Percutaneous Coronary Intervention

Introduction
Coronary arteries that tunnel through the myocardium are seen as often as 40–80% on autopsy; however, functional myocardial bridging is less commonly observed on angiography (0.5–16%) and can range from 4 to 80 mm in length (1-4). Although

© 2014 American College of Cardiology Foundation. Published by Elsevier Inc. All rights reserved.
Address for correspondence: Habib Samady, MD, FACC, FSCAI, Professor of Medicine, Director, Interventional Cardiology, Emory University School of Medicine, 1364 Clifton Road, Suite F606, Atlanta, GA 30322, Telephone: (404) 778-1237, Fax: (404) 712-5622, hsamady@emory.edu.
Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
myocardial bridges can be found in any epicardial artery, 67-98% occur in the left anterior descending coronary artery (LAD) (5,6). Bridges have been described as superficial or deep based on three observations: 1) they range from 0.3 to 28 mm in depth (4,5), 2) anatomically they consist of either superficial myocardial fibers that traverse over the LAD or deep fibers that encircle the LAD (5,7) and 3) bridges >5 mm deep are less amenable to surgical myotomy (8). The hemodynamic impact of myocardial bridging depends on the thickness and length of the bridge, orientation of the bridge relative to myocardial fibers and presence of loose connective or adipose tissue around the bridged segment.

Pathophysiology

Autopsy and intravascular ultrasound (IVUS) studies demonstrate that the intramural and distal segments of bridged vessels remain free from atherosclerotic disease while the proximal segment of the vessel is prone to developing atherosclerosis (9,10). Biomechanical forces may explain these observations. At the entrance of a myocardial bridge, fluid mechanics play an important role in plaque formation as disturbed near-wall blood flow patterns are a central factor in the spatial distribution of atherosclerosis (11,12). Low and oscillatory wall shear stress (WSS) are associated with increased vascular cell adhesion molecule-1 expression (11,13) and reactive oxygen species production (14), as well as the development of a pro-atherogenic endothelial cell phenotype (12). Indeed, autopsy studies have demonstrated that coronary segments immediately proximal to myocardial bridges, where WSS is low, demonstrate structurally dysfunctional, flat and polygonal endothelial cells whereas endothelial cells lining bridged segments, where WSS is physiologic or high, are structurally intact (15). Clinical studies in patients with mild atherosclerosis but without bridging have demonstrated greater plaque progression in segments with low WSS compared to physiologic or high WSS (16). In a case-control series comparing patients with bridging to controls (17), wall shear rate, the velocity gradient perpendicular to the wall, was found to be lower proximal to the bridge as compared to within the bridge.

Figure 1 represents a computational fluid dynamics model at end-systole of the LAD in a patient with a symptomatic myocardial bridge revealing an area of relative low WSS proximal and distal to the bridge and high WSS within the bridge. Enhanced myocardial compression at the bridge entrance also results in abrupt breakage of the propagating antegrade systolic wave, disrupting blood flow patterns, exacerbating the low WSS, and intensifying endothelial injury and the stimuli for plaque formation (18). Another proposed mechanism of plaque formation proximal to a myocardial bridge involves solid mechanical forces that result from the motion and deformation of the coronary tree and myocardial material properties. Specifically, compression within the bridge and severe vessel angulation at the junction of the bridge result in a heterogeneous stress field in the proximal segment. The induced stresses are hypothesized to be conducive to plaque development and possible fissuring in the proximal segments (18).

Within the bridge, increased mechanical loads likely contribute to constrictive vascular remodeling as an attempt to restore loads to homeostatic levels (19). These mechanisms are amplified with diastolic dysfunction that occurs with left ventricular hypertrophy. In addition, separation of the bridged segment from perivascular adipose tissue in the
epicardium that is associated with pro-inflammatory cytokines and adipokines may be a protective mechanism against the development of atherosclerosis (20). These factors likely contribute to plaque formation proximal to myocardial bridges and exert an atheroprotective role within the bridge. The relative lack of atherosclerosis observed distal to myocardial bridges despite presence of low WSS is not well understood. Clearly, complex and dynamic biomechanical factors influence the blood flow within and at the exit of the bridge that in aggregate appear to attenuate the pro-atherosclerotic stimulus of low WSS observed distal to the bridge.

Additional pathophysiologic changes can induce symptoms of myocardial ischemia in previously asymptomatic patients (figure 2). First, increasing left ventricular diastolic dysfunction associated with aging, hypertension, and coronary atherosclerosis can exacerbate the supply-demand mismatch imposed by the bridge. Second, left ventricular hypertrophy development can increase compression and reduce the coronary microvascular reserve. Third, coronary vasospasm, microvascular dysfunction, or endothelial dysfunction related to cardiovascular risk factors combined with the bridge can result in myocardial ischemia. Fourth, plaque development proximal to the bridge can augment coronary obstruction by the bridge. Fifth, the negative remodeling within the bridge can reduce myocardial flow. Each of these factors can contribute to a varying degree to the development of symptoms in patients with myocardial bridging.

More recently, it has been recognized that myocardial ischemia is not purely related to systolic vascular compression. Indeed, systolic vessel compression has been shown to persist into mid-to-late diastole (2). The hemodynamic disturbance imposed by this persistent diastolic luminal narrowing was corroborated by increases in both average peak-flow velocity and average diastolic peak-flow velocity, with only minor changes in systolic blood flow within the bridged segment of the coronary artery. These data suggest that both systolic and diastolic flow impairment contribute to myocardial supply to demand mismatch in patients with myocardial bridging.

Clinical Presentation

Although myocardial bridging can be an incidental finding on angiography or autopsy, symptomatic patients who have myocardial bridges as their only cardiac abnormality may present with myocardial ischemia (21), acute coronary syndromes (22-24), coronary spasm (21,25), exercise-induced dysrhythmias like supraventricular tachycardia (24), ventricular tachycardia (26,27) or atrioventricular conduction block (28), myocardial stunning (29), transient ventricular dysfunction (30), syncope (24,27) or even sudden death (31,32).

Diagnosis

A number of diagnostic modalities have been deployed to investigate the anatomic and physiologic significance of myocardial bridging (Table 1). Because of the lack of a true gold standard for diagnosing myocardial bridging, the reported diagnostic accuracies are variable.
Non-Invasive Diagnostic Techniques

Multiple-slice computed tomography (MSCT), stress single photon emission computed tomography (SPECT) and stress echocardiography have been used in the diagnosis of myocardial bridging. MSCT defines bridges as segments surrounded by myocardium (33). Recent developments allowing for physiologic assessment by MSCT may enhance its diagnostic utility for identifying hemodynamically significant bridges. Stress SPECT can detect reversible myocardial perfusion defects in patients with myocardial bridging and relate the amount of ischemia to the degree of systolic luminal narrowing (34,35). Contrast stress echocardiography has been reported for myocardial bridge detection but is less validated (36).

Invasive Diagnostic Techniques

On angiography, diagnosis depends on the diameter change between systole and diastole within the bridged coronary segment. A significant “milking effect” (Figure 3) is present when there is ≥70% reduction in minimal luminal diameter (MLD) during systole and persistent ≥35% MLD reduction during mid-to-late diastole (2). Systolic narrowing at the bridge can be accentuated by intracoronary nitroglycerin injection by vasodilating adjacent non-bridged coronary segments (Figure 4) (9,37).

Adjunctive intravascular imaging and physiology can contribute to our clinical evaluation and understanding of the complex pathophysiology of bridging. On IVUS, the characteristic finding is the “half-moon” sign: an echolucent area present only between the bridged coronary segment and epicardial tissue that persists throughout the cardiac cycle (Figure 5) (9). Additionally, IVUS can characterize sub-angiographic atherosclerosis proximal to bridges.

Coronary physiologic measurements across a myocardial bridge during pharmacologic infusion can be valuable for 1) evaluation of the hemodynamic significance of fixed obstruction associated with the bridge, 2) simulation of dynamic myocardial obstruction that could contribute to ischemic symptoms and 3) unmasking concomitant endothelial dysfunction or coronary vasospasm within the bridged segment that could also be clinically relevant. The bridged segment produces a distinctive flow velocity called the “finger tip” phenomenon (Figure 6). The abrupt velocity acceleration in early diastole results from a decrease in distal microvascular resistance as the myocardium untwists during isovolumetric relaxation concomitant with continuing myocardial compression of the bridged coronary segment. Rapid deceleration in velocity ensues as the bridge muscle relaxes and the lumen cross-sectional area increases. Velocity plateau occurs when the artery has fully reopened (1,18).

For the evaluation of hemodynamically significant stenoses, fractional flow reserve (FFR) can be measured (38). A patient with a myocardial bridge with an FFR <0.75 likely has ischemia associated with that bridge. As in non-bridged patients, there is a grey zone of ischemia from FFR 0.75-0.80. For a patient with an abnormal but non-ischemic FFR (>0.80), intravenous dobutamine administration can lead to higher pressure gradients (and sometimes ventricularization of the distal pressure tracing) and reproduction of their angina.
symptoms, which would then suggest a clinically significant myocardial bridge (39). If concomitant velocity data are available, higher average peak velocity with infusion of dobutamine (Figure 7B) as compared to adenosine (Figure 7A) in association with the higher pressure gradients suggests further luminal narrowing, lending further support to the clinical significance of the myocardial bridge. Finally, vasoconstriction with intracoronary acetylcholine infusion (off-label use) can unmask concomitant endothelial dysfunctional or coronary vasospasm.

Classification

The Schwarz classification (Table 2) can serve as a guide for directing therapy for patients with myocardial bridging since it has been linked to clinical outcomes following pharmacological and invasive interventions (40). Schwarz type A patients need no treatment, whereas types B and C patients show significant symptomatic improvement with β-blockers or calcium channel blockers at five-year follow-up. Type C patients refractory to medical therapy may be considered for revascularization of the myocardial bridge.

Management

Treatment of symptomatic patients with myocardial bridging consists primarily of pharmacologic therapy although percutaneous coronary intervention (PCI), myotomy, or coronary artery bypass grafting surgery (CABG) can be considered for selected patients refractory to maximal medical therapy.

A: Pharmacological Therapy

Aggressive risk factor modification is advocated and antiplatelet therapy should be considered in patients with myocardial bridging as they are at increased risk of developing atherosclerosis. One approach to individualizing the need for antiplatelet therapy would be to perform MSCT to identify subclinical atherosclerosis. For symptomatic patients, β-blockers remain the mainstay of treatment and relieve the hemodynamic disturbance caused by the myocardial bridge by decreasing heart rate, increasing diastolic coronary filling period, and decreasing contractility and compression of the coronary arteries (2,41). Calcium channel blockers are also frequently used and, in addition to the aforementioned pharmacologic effects of β-blockers, may have vasodilatory effects that might be beneficial in patients with concomitant vasospasm. Head-to-head comparison of β-blockers and calcium channel blockers or randomized clinical trials of outcome benefit of β-blockers are not available.

In contrast, pure vasodilating agents such as nitroglycerin should be used cautiously in patients with myocardial bridges. Although nitrates have antispasmodic properties and can decrease preload, they can worsen symptoms by intensifying systolic compression of the bridged segment and vasodilating segments proximal to the bridge (figure 4), thereby exacerbating retrograde flow in the proximal segment and reducing the myocardial ischemic threshold (9,37). Vasodilators should thus be avoided unless there is significant co-existing coronary vasospasm.
B: Percutaneous Coronary Intervention

Stent implantation in symptomatic patients with myocardial bridges can ameliorate peak intracoronary systolic pressure and vessel compression, normalize flow and abolish symptoms (42); however, concerns regarding perforation during stent deployment (21,43), stent fracture (44), in-stent restenosis (44-48) and stent thrombosis (49) have limited their use in this condition. Investigations focusing on in-stent restenosis are summarized in Table 3 and suggest two conclusions: 1) stent implantation in patients with symptomatic myocardial bridges result in high rates of early in-stent restenosis which may be related to bridge-associated decreased lumen area and 2) compared to PCI with bare metal stents (BMS), PCI with drug-eluting stents (DES) have lower rates of target vessel revascularization (TVR).

Higher restenosis rates were demonstrated in patients undergoing PCI with BMS for symptomatic isolated myocardial bridging in one prospective study of 11 patients which reported early in-stent restenosis requiring TVR in 4 patients (45) and in another investigation comparing a similar cohort of 12 patients to 39 patients who underwent BMS implantation for atherosclerotic lesions in the LAD (46). While DES implantation results in lower TVR rates than BMS implantation, restenosis still occurs more frequently in PCI for symptomatic myocardial bridging than in PCI for atherosclerotic lesions. A small study that compared implantation of DES (n=8) versus BMS (n=4) in symptomatic patients refractory to maximal medical therapy reported lower TVR rates in the DES cohort than in the BMS group, but both groups had higher rates relative to historical controls (47). Another investigation evaluated PCI with predominantly DES in 70 patients with both myocardial bridges and LAD lesions and divided them into two cohorts based on whether the implanted stents ended proximal to a myocardial bridge or extended into the bridged segment. The TVR rate was significantly higher in patients with stents extending into the bridge compared to patients with stents ending proximal to the myocardial bridge (29% vs. 3%) (48). Interestingly, minimum stent cross-sectional area was also significantly smaller for stents extending into the bridged segment as opposed to those that ended proximal to the bridge (4.8 mm$^2$ vs. 5.8 mm$^2$). A recent prospective study of PCI with DES for symptomatic isolated myocardial bridging reported 3/15 patients requiring revascularization within 6 months post-procedure but no further complications (43).

Any rationale for PCI in selected myocardial bridge patients would be to treat plaque proximal to the bridge as well as the negative remodeling and dynamic obstruction within the bridged segment. While contemporary metallic stent platforms can provide sufficient scaffolding to achieve adequate diastolic and systolic flow, sustained stress over time may result in stent fracture, restenosis, or thrombosis. Concerns have also been raised about the radial strength of bioabsorbable stents. Future bioabsorbable scaffolds could be designed with sufficient radial strength to safely achieve greater acute luminal gain in the intramyocardial artery while withstanding the systolic compression pressure during the bioabsorption phase, which after resorption could leave behind a much larger lumen supported by a residual thin fibrous endoluminal layer. Whether scaffolds with these biomechanical properties can be developed and withstand the scrutiny of angiographic and outcome studies remain to be seen.
Taken together, although there are no randomized controlled trials of optimal medical therapy versus optimal medical therapy and contemporary PCI with DES, medical therapy appears to be superior to PCI. Ischemia guided revascularization using DES may be considered on a case-to-case basis for symptomatic patients refractory to maximal medical therapy and who are not optimal surgical candidates.

**C: Surgical Treatment**

Surgical intervention involves either supraarterial myotomy or CABG. In a typical myotomy case (Figure 8), the cardiac muscle is dissected carefully and completely. Potential complications of myotomy include wall perforation, ventricular aneurysm formation and post-operative bleeding. Conversely, the major concern of CABG with regards to myocardial bridges is graft failure.

Studies investigating the effectiveness of myotomy or CABG in patients with symptomatic bridging refractory to medical therapy are summarized in Table 4. Two retrospective studies on myotomy described overall successful operations; however, one series reported accidental right ventricular wall perforation in 2/9 patients (50) and the other study reported that 1/26 patients underwent CABG for post-operative angina with LAD narrowing (51). Regarding CABG, one investigation reported no complications (52) while the second described 6/39 patients with recurrent angina and 15/39 patients with graft occlusions on follow-up (53). Grafting with the LIMA was more likely to result in occlusion compared to grafting with the saphenous vein (12 vs. 3 patients), leading the authors to conclude that grafting with the saphenous vein was preferable. This is in contrast to a previous report recommending the LIMA as the preferred graft for CABG (4).

Investigations comparing the effectiveness between myotomy and CABG in patients with symptomatic myocardial bridges consist of one study on 31 patients (4,54) and an even smaller series of 11 patients (55). In the first investigation, one myotomy case was converted to CABG after accidental right ventricular wall perforation. Among 21/31 patients (either myotomy or CABG) who underwent follow-up angiography, all demonstrated restoration of distal coronary blood flow (4). In the second study, 2/11 patients experienced atypical chest pain and were managed medically (55).

While both myotomy and CABG are reasonable initial choices, it is unclear which procedure is superior. On the one hand, because myotomy attempts to correct the underlying pathology, it may be the treatment of choice for patients who have symptomatic myocardial bridging refractory to medical therapy, 25% systolic coronary compression on angiography or evidence of myocardial ischemia or infarction (4). On the other hand, CABG is favored over myotomy in cases of extensive (>25 mm) or deep (>5 mm) myocardial bridges (the risk of myotomy can be considerable), or when the bridged coronary segment fails to decompress completely in diastole (myotomy is unlikely to correct the persistent diastolic compression) (4,8). Importantly, there are no randomized clinical trials comparing intensification of medical therapy to surgical intervention. These limited data suggest that surgical therapy, either myotomy or CABG, appears safe and effective in symptomatic patients with myocardial bridging who are refractory to medical therapy.
Conclusion

Patients with myocardial bridging are commonly encountered clinically who may present with exertional symptoms of myocardial ischemia, syncope, and even sudden death. An array of non-invasive and invasive diagnostic modalities that have shed light on the pathophysiology of myocardial bridging can be deployed to evaluate symptomatic patients. Medical therapy with β-blockers and calcium channel blockers remain the mainstay in treatment. For select patients refractory to intensified medical therapy, surgical intervention, or less preferably PCI with DES, can be considered. Larger registries and randomized clinical trials are warranted to shed light on optimal strategies for patients with myocardial bridging refractory to medical therapy.

Acknowledgments

We gratefully acknowledge Clare Wang for her artistic contribution to Figure 2 and Bill Gogas, MD for his editorial suggestions.

Funding Sources

Dr. Hung is supported by the Ruth L. Kirschstein National Research Service Awards training grant (5T32HL007745). Dr. Mekonnen is supported by a grant from the National Heart, Lung, and Blood Institute of the National Institutes of Health (PO1HL101398). Dr. Timmins is supported by the American Heart Association Postdoctoral Fellowship (11POST210012). Dr. Guyton is a consultant for Medtronic, Inc. (Minneapolis, MN). Dr. Samady receives research funding from Volcano Corporation (San Diego, CA) and St. Jude Medical (St. Paul, MN). The other authors have no relationships with industry that are relevant to the content of this paper to disclose.

Abbreviations

CABG     coronary artery bypass grafting
FFR      fractional flow reserve
IVUS     intravascular ultrasound
LAD      left anterior descending coronary artery
MLD      minimal luminal diameter
MSCT     multiple-slice computed tomography
PCI      percutaneous coronary intervention
SPECT    single photon emission computed tomography
TVR      target vessel revascularization
WSS      wall shear stress

References


J Am Coll Cardiol. Author manuscript; available in PMC 2015 June 10.


Figure 1. Relative Wall Shear Stress Profile of the Left Anterior Descending Artery in the Context of Myocardial Bridging
Relative WSS profile of a 3-dimensional angiographically reconstructed left anterior descending coronary artery during systole from a patient with myocardial bridging. Coronary segments proximal and distal to myocardial bridge show relative low WSS as compared to the bridged segment. S1: First septal branch; WSS: Wall shear stress.
Figure 2. Schematic Diagram of the Effects of Aging on the Myocardial Bridge

A: Heart with myocardial bridging, early stage. B: Longitudinal view of the bridged vessel. C: Cross-sectional view of the vessel in the middle of the myocardial bridge. A': Heart with myocardial bridging, late stage, with ventricular hypertrophy and diastolic dysfunction. B': Longitudinal view of the bridged vessel, with hypertrophied muscle and plaque progression proximal to the bridge. C': Cross-sectional view of the vessel in the middle of the myocardial bridge showing hypertrophied muscle and the negative remodeling of the vessel with decreased lumen diameter. Images were drawn by Clare Wang.
Figure 3. “Milking Effect” in Coronary Angiography

A: Systolic compression of myocardial bridges, the “milking effect”  
B: Subsequent increase in vessel lumen diameter during diastole. White arrows represent areas of myocardial bridging.
Figure 4. Systolic Narrowing at the Myocardial Bridge Accentuated By Intracoronary Nitroglycerin

A: Systolic compression of myocardial bridge at baseline. B: Systolic narrowing at the myocardial bridge accentuated by intracoronary injection of nitroglycerin. White arrows point to area of myocardial bridging.
Figure 5. Intravascular Ultrasound “Half-moon” Sign
In this example of the “half-moon” sign, the echolucent area is present only between the bridged coronary segment and the epicardial tissue.
Figure 6. Finger Tip Phenomenon During Intracoronary Doppler Measurements

A: Example of normal flow pattern. B: Example of the “finger tip” phenomenon, a characteristic velocity profile demonstrating abrupt early diastolic acceleration, rapid mid-diastolic deceleration, and mid-to-late diastolic plateau.
Figure 7. Intracoronary Hemodynamic Measurements Distal to a Myocardial Bridge
Coronary blood velocity (blue tracing), proximal pressure (Pa, red tracing) and distal pressure (Pd, yellow tracing) measurements distal to a myocardial bridge. Electrocardiogram (white tracing). Blue circles indicate the tracings' portions magnified above each circle. A: adenosine (140 mcg/Kg/min), FFR=0.83, APV=28 cm/s; HR=96 bpm. B: dobutamine (60 mcg/Kg/min), FFR=0.82, APV=38 cm/s, HR=122 bpm. APV: Average peak blood velocity; BPM: Beats per minute; FFR: Fractional flow reserve; HR: Heart rate.
Figure 8. Myotomy Procedure

A: View before incision showing intramyocardial LAD. B: Fat incised, showing LAD (yellow arrows) and the bridging muscle (blue arrows). C: Unroofed LAD with cut ends of bridging muscle (blue arrows). LAD: Left anterior descending artery.
Table 1
Myocardial Bridging Diagnostic Modalities

<table>
<thead>
<tr>
<th>Diagnostic Technique</th>
<th>Diagnostic Sign</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative Coronary Angiography</td>
<td>Milking Effect</td>
<td>Commonly used Cornerstone technique Anatomic assessment</td>
<td>Invasive No physiologic value</td>
</tr>
<tr>
<td>Intravascular Ultrasound</td>
<td>Half-Moon</td>
<td>Identify: - Proximal plaque - Negative arterial remodeling - Extent of phasic arterial compression</td>
<td>Not commonly used Invasive No physiologic value</td>
</tr>
<tr>
<td>Intracoronary Doppler Measure (with pharmacologic infusion)</td>
<td>Finger Tip</td>
<td>Hemodynamic evaluation of: - Proximal plaque - Negative remodeling</td>
<td>Longer procedural time Invasive Pharmacological side effects No established FFR cutoff with adenosine or dobutamine Off-label use of acetylcholine</td>
</tr>
<tr>
<td>Intracoronary Pressure Measure (with pharmacologic infusion)</td>
<td>Hemodynamic Limitation (FFR &lt; 0.75-0.8)</td>
<td>Simulation of dynamic myocardial obstruction Endothelial function testing/coronary vasospasm assessment</td>
<td>Not readily available Radiation exposure</td>
</tr>
<tr>
<td>Multiple-Slice Computed Tomography</td>
<td>Completely or partially surrounded coronary segment by myocardium on axial and multiplanar reformed images</td>
<td>Superior to angiography Non-invasive Promising physiologic value in the near future</td>
<td>No established FFR cutoff with adenosine or dobutamine Off-label use of acetylcholine</td>
</tr>
<tr>
<td>Single Photon Emission Computed Tomography</td>
<td>Reversible stress induced myocardial perfusion defect in the absence of angiographic coronary artery disease</td>
<td>Physiological assessment of myocardial bridge stress induced ischemia</td>
<td>Not readily available Radiation and contrast exposure</td>
</tr>
<tr>
<td>Contrast Stress Echocardiography</td>
<td>Reversible perfusion defects in angiographically normal arteries</td>
<td>Readily available Non-invasive Physiologic assessment</td>
<td>No anatomic value Contrast exposure</td>
</tr>
</tbody>
</table>

* FFR: Fractional Flow Reserve
Table 2

Schwarz Classification for Myocardial Bridges and Treatment

<table>
<thead>
<tr>
<th>Schwarz Type</th>
<th>Criteria</th>
<th>Objective signs of Ischemia</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Incidental Finding on Angiography</td>
<td>−</td>
<td>None</td>
</tr>
<tr>
<td>B</td>
<td>Ischemia on Stress Test</td>
<td>+</td>
<td>BB or CCB</td>
</tr>
<tr>
<td>C</td>
<td>Altered Intracoronary Hemodynamics (QCA/CFR/Doppler)</td>
<td>+/-</td>
<td>BB or CCB ± Revascularization</td>
</tr>
</tbody>
</table>

*BB: beta-blocker;
†CCB: calcium channel blocker;
‡CFR: Coronary Flow Reserve;
§QCA: quantitative coronary angiography.
### Table 3

**Studies of In-stent Restenosis Related to Percutaneous Coronary Intervention for Myocardial Bridging**

<table>
<thead>
<tr>
<th>Author</th>
<th>Study Cohort</th>
<th>Intervention</th>
<th>Follow-Up</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klues et al.</td>
<td>MB (n=3)</td>
<td>BMS</td>
<td>7 weeks</td>
<td>No ISR or MACE</td>
</tr>
<tr>
<td>Haager et al.</td>
<td>MB (n=11)</td>
<td>BMS</td>
<td>2 years</td>
<td>45% ISR (7 weeks)</td>
</tr>
<tr>
<td>Kursaklioglu et al.</td>
<td>MB (n=12) non-MB (n=39)</td>
<td>BMS</td>
<td>6 months</td>
<td>ISR 67% in MB vs. 28% in non-MB</td>
</tr>
<tr>
<td>Kunamneni et al.</td>
<td>MB (n=12)</td>
<td>4 BMS 8 DES</td>
<td>1 year</td>
<td>ISR 75% in BMS vs. 25% in DES</td>
</tr>
<tr>
<td>Tsujita et al.</td>
<td>MB (n=70) 34% stents covering MB 66% stents not covering MB</td>
<td>4 BMS 66 DES</td>
<td>1 year</td>
<td>MB Stent Group: 33% MACE non-MB Stent Group: 11% MACE</td>
</tr>
<tr>
<td>Ernst et al.</td>
<td>MB (n=15)</td>
<td>DES</td>
<td>5 years</td>
<td>1 perforation during stent implantation 19% ISR (6 months)</td>
</tr>
</tbody>
</table>

*BMS: Bare metal stent;  
†DES: Drug-eluting stent;  
‡ISR: In-stent restenosis;  
§MACE: Major adverse cardiac events;  
∥MB: Myocardial bridge.*
Table 4

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Study Design</th>
<th>Procedure</th>
<th>Follow-Up Period</th>
<th>Immediate post-operative results</th>
<th>Follow-up results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iversen et al. 1992 (50) (abstract)</td>
<td>Retrospective 9 pts</td>
<td>Myotomy</td>
<td>In hospital</td>
<td>2 pts with right ventricular perforation. All pts survived operation. Post-operative studies showed flow restoration</td>
<td>None</td>
</tr>
<tr>
<td>Rezayat et al. 2006 (51) (abstract)</td>
<td>Retrospective 26 pts</td>
<td>Myotomy</td>
<td>7-81 months (mean 34.2 months)</td>
<td>1 pt had post-operative angina with angiography showing narrowing in LAD and subsequently underwent CABG with LIMA graft.</td>
<td>2 pts with angina, treated medically. No MACE</td>
</tr>
<tr>
<td>Wan &amp; Wu 2005 (54)</td>
<td>Retrospective 19 pts</td>
<td>4 PCI with BMS 8 CABG 7 myotomy</td>
<td>6-75 months (mean 23.5 months)</td>
<td>No complications</td>
<td>2/4 PCI pts had in-stent restenosis. One subsequently underwent CABG. No MACE in surgical groups</td>
</tr>
<tr>
<td>Wu &amp; Xu 2007 (4)</td>
<td>Retrospective 31 pts</td>
<td>16 CABG 15 myotomy</td>
<td>3-115 months (mean 31 months)</td>
<td>1 pt with right ventricular perforation, successfully converted to CABG</td>
<td>21/31 pts (11 CABG, 10 myotomy) underwent follow-up angiography showing restoration of flow. No MACE</td>
</tr>
<tr>
<td>Huang et al. 2007 (55)</td>
<td>Retrospective 11 pts Isolated myocardial bridge</td>
<td>8 CABG with LIMA graft 3 myotomy</td>
<td>6-120 months (median 35.3 months)</td>
<td>1 pt with right ventricular perforation, successfully converted to CABG</td>
<td>2 pts experienced atypical chest pain, treated medically. No MACE</td>
</tr>
<tr>
<td>Sun et al. 2012 (52)</td>
<td>Retrospective 13 patients Isolated myocardial bridge</td>
<td>CABG with LIMA graft</td>
<td>24-55 months</td>
<td>No complications</td>
<td>Pts were either CCS class 0 or 1. 7 pts underwent CCTA at 1 yr, no stenoses. No MACE</td>
</tr>
<tr>
<td>Bockeria, et al. 2013 (53)</td>
<td>Retrospective 39 pts Isolated myocardial bridge</td>
<td>CABG -19 with SVG -20 with LIMA graft</td>
<td>LIMA 6-23 months SVG 2-25 months</td>
<td>2 pts underwent repeat sternotomy for bleeding. 2 pts required ionotropes</td>
<td>6/39 pts had recurrent angina. Angiography at 12 months showed occlusions in 12 LIMA grafts and 3 SVG. No mortality</td>
</tr>
</tbody>
</table>

* BMS: Bare metal stent;
† CABG: Coronary artery bypass grafting;
‡ CCS: Canadian Cardiovascular Society;
§ CCTA: Cardiac computed tomography angiography;
∥ LAD: Left anterior descending artery;
LIMA: Left internal mammary artery;
MACE: Major adverse cardiac events;
PCI: Percutaneous coronary intervention;
Pts: patients;
SVG: Saphenous vein graft.