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Myocardial Bridging

Contemporary Understanding of Pathophysiology With Implications for Diagnostic and Therapeutic Strategies

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Patients with myocardial bridging 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. (J Am Coll Cardiol 2014;63:2346–55)

Coronary arteries that tunnel through the myocardium are seen in as many as 40% to 80% of cases on autopsy; however, functional myocardial bridging is less commonly observed on angiography (0.5% to 16.0%) and can range from 4 to 80 mm in length (1–4). Although myocardial bridges can be found in any epicardial artery, 67% to 98% occur in the left anterior descending coronary artery (LAD) (5,6). Bridges have been described as superficial or deep on the basis of 3 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, the orientation of the bridge relative to myocardial fibers, and the presence of loose connective or adipose tissue around the bridged segment.

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Pathophysiology

Autopsy and intravascular ultrasound studies have shown 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 because 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 expression of vascular cell adhesion molecule 1 (11,13) and reactive oxygen species production (14) as well as the development of a proatherogenic endothelial cell phenotype (12). Indeed, autopsy studies have shown that coronary segments immediately proximal to myocardial bridges, where WSS is low, have structurally dysfunctional, flat and polygonal endothelial cells, whereas endothelial cells lining bridged segments, where WSS is physiological or high, are structurally intact (15). Clinical studies in patients with mild atherosclerosis but without bridging have shown greater plaque progression in segments with low WSS compared with physiological or high WSS (16). In a case-control series comparing patients who had bridging with control patients (17), the wall shear rate, which is the velocity gradient perpendicular to the wall, was found to be lower proximal to the bridge compared with within the bridge.

Figure 1 shows a computational fluid dynamics model at end-systole of the LAD in a patient with a symptomatic myocardial bridge revealing an area of relatively 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 proinflammatory 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 the 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 proatherosclerotic stimulus of low WSS observed distal to the bridge.

Additional pathophysiological changes can induce symptoms of myocardial ischemia in previously asymptomatic patients (Fig. 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, development of left ventricular hypertrophy 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

Abbreviations and Acronyms

BMS = bare-metal stent(s)
CABG = coronary artery bypass grafting
DES = drug-eluting stent(s)
FFR = fractional flow reserve
LAD = left anterior descending coronary artery
MSCT = multiple-slice computed tomography
PCI = percutaneous coronary intervention
TVR = target vessel revascularization
WSS = wall shear stress

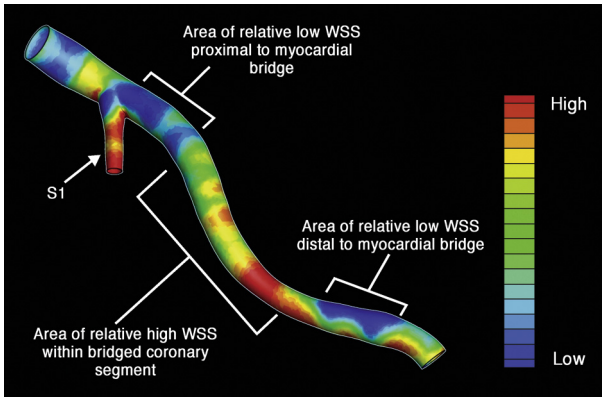

Figure 1 **Relative WSS Profile of the LAD in the Context of Myocardial Bridging**

Relative WSS profile of a 3-dimensional angiographically reconstructed LAD during systole from a patient with myocardial bridging. Coronary segments proximal and distal to the myocardial bridge show relatively low WSS compared with the bridged segment. LAD = left anterior descending coronary artery; S1 = first septal branch; WSS = wall shear stress. Image created by Craig Skaggs.

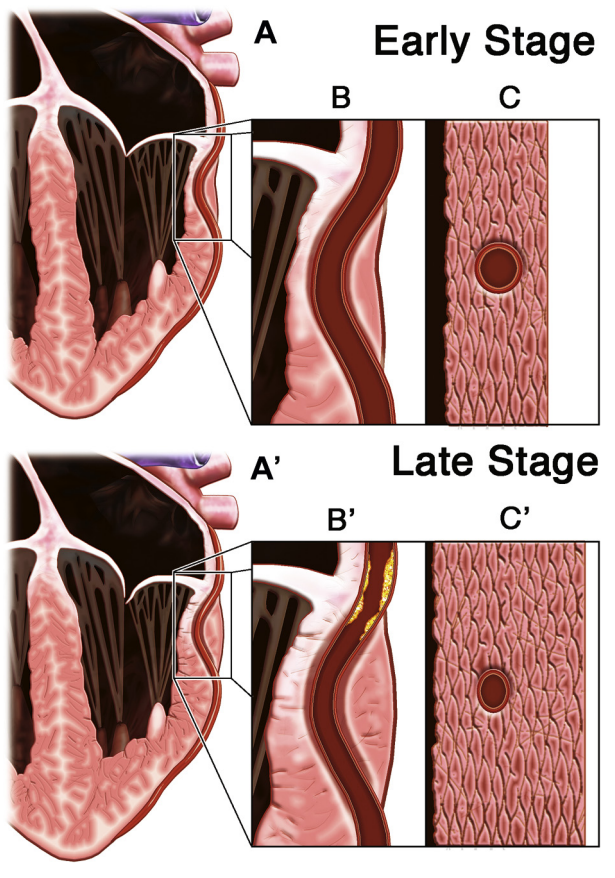

Figure 2 **Schematic Diagram of the Effects of Aging on the Myocardial Bridge**

(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 negative remodeling of the vessel with decreased lumen diameter. Images created by Clare Wang and Craig Skaggs.

Table 1 Diagnostic Modalities for Myocardial Bridging

Diagnostic Technique	Diagnostic Sign	Advantages	Disadvantages
Quantitative coronary angiography	Milking effect	Commonly used Cornerstone technique Anatomic assessment	Invasive No physiological value
Intravascular ultrasound	Half-moon	Identify • Proximal plaque • Negative arterial remodeling • Extent of phasic arterial compression	Not commonly used Invasive No physiological value
Intracoronary Doppler measure (with pharmacological infusion) Intracoronary pressure measure (with pharmacological infusion)	Fingertip Hemodynamic limitation (FFR <0.75 to 0.8)	Hemodynamic evaluation of • Proximal plaque • Negative remodeling Simulation of dynamic myocardial obstruction Endothelial function testing/coronary vasospasm assessment	Longer procedural time Invasive Pharmacological side effects No established FFR cutoff with adenosine or dobutamine Off-label use of acetylcholine
Multiple-slice computed tomography	Completely or partially surrounded coronary segment by myocardium on axial and multiplanar reformatted images	Superior to angiography Noninvasive Promising physiological value in the near future	Not readily available Radiation exposure
Single-photon emission computed tomography	Reversible stress-induced myocardial perfusion defect in the absence of angiographic coronary artery disease	Physiological assessment of myocardial bridge stress-induced ischemia	Not readily available Radiation and contrast exposure
Contrast stress echocardiography	Reversible perfusion defects in angiographically normal arteries	Readily available Noninvasive Physiological assessment	No anatomic value Contrast exposure

FFR = fractional flow reserve.

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-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

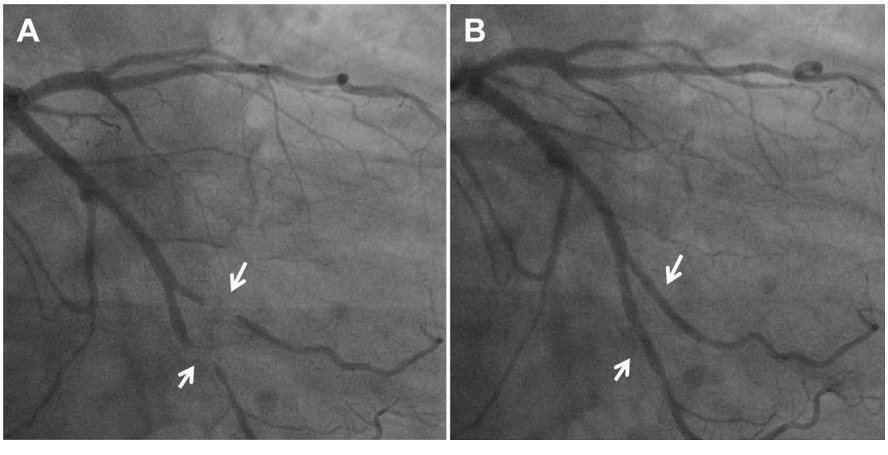

Figure 3 "Milking Effect" in Coronary Angiography

(A) Systolic compression of myocardial bridges: the "milking effect." **(B)** Subsequent increase in vessel lumen diameter during diastole. **White arrows** indicate areas of myocardial bridging.

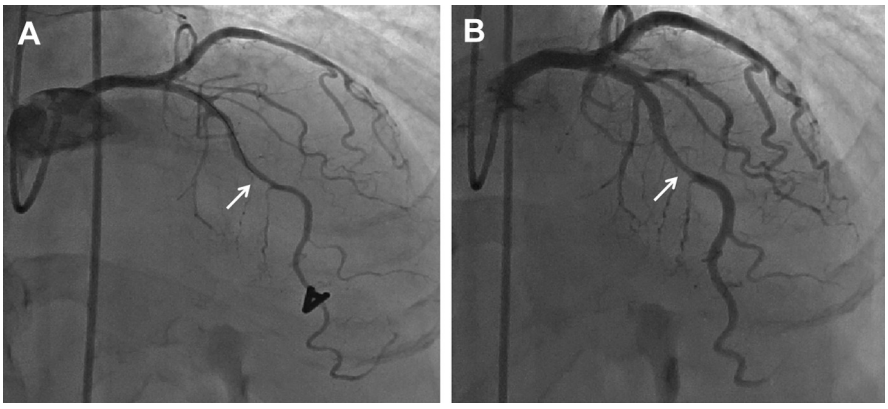

Figure 4 Systolic Narrowing at the Myocardial Bridge Accentuated by Intracoronary Nitroglycerin

(A) Systolic compression of the myocardial bridge at baseline. **(B)** Systolic narrowing at the myocardial bridge accentuated by intracoronary injection of nitroglycerin. **White arrows** indicate the area of myocardial bridging.

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 such as 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).

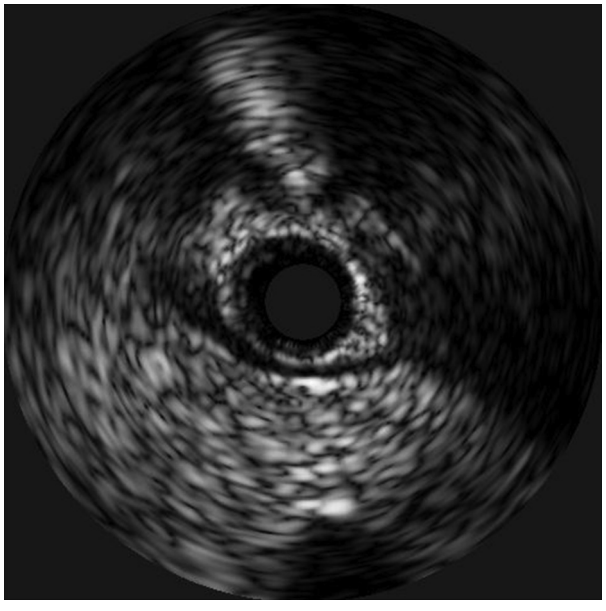

Figure 5 Intravascular Ultrasound "Half-Moon" Sign

In this example of the "half-moon" sign, the echolucent area is present only between the bridged coronary segment and the epicardial tissue.

Diagnosis

A number of diagnostic modalities have been used to investigate the anatomic and physiological 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.

Noninvasive diagnostic techniques. Multiple-slice computed tomography (MSCT), stress single-photon emission computed tomography, 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 physiological assessment by MSCT may enhance its diagnostic utility for identifying hemodynamically significant bridges. Stress single-photon emission computed tomography 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 used for detection of myocardial bridging but is not as well validated (36).

Invasive diagnostic techniques. On angiography, diagnosis depends on the change in diameter between systole and diastole within the bridged coronary segment. A significant "milking effect" (Fig. 3) is present when there is $\geq$70% reduction in minimal luminal diameter during systole and persistent $\geq$35% reduction in minimal luminal diameter during mid-to-late diastole (2). Systolic narrowing at the bridge can be accentuated by intracoronary injection of nitroglycerin by vasodilating adjacent nonbridged coronary segments (Fig. 4) (9,37).

Adjunctive intravascular imaging and physiology can contribute to our clinical evaluation and understanding of the complex pathophysiology of bridging. On

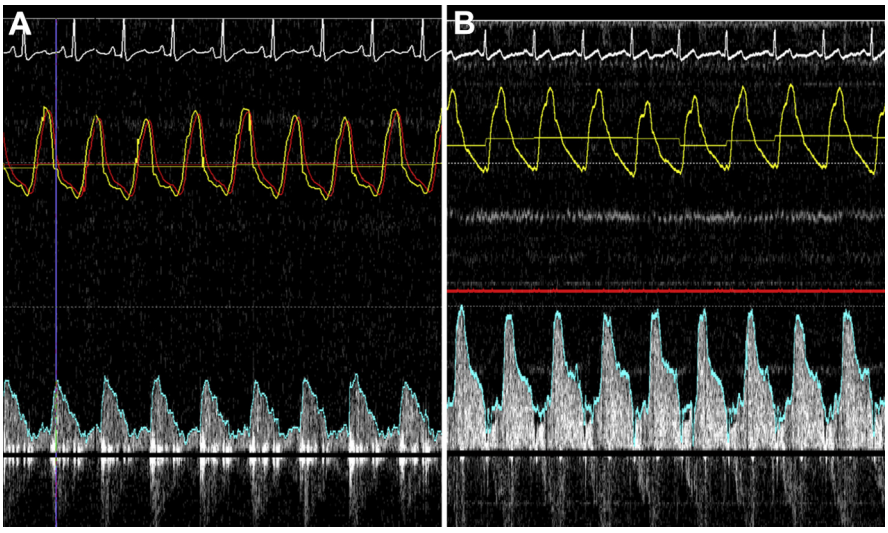

Figure 6 Fingertip Phenomenon During Intracoronary Doppler Measurements

(A) Example of a normal flow pattern. **(B)** Example of the "fingertip" phenomenon, a characteristic velocity profile showing abrupt early diastolic acceleration, rapid mid-diastolic deceleration, and mid-to-late diastolic plateau.

intravascular ultrasound 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 (Fig. 5) (9). Additionally, intravascular ultrasound can characterize subangiographic atherosclerosis proximal to bridges.

Coronary physiological measurements across a myocardial bridge during pharmacological infusion can be valuable for:

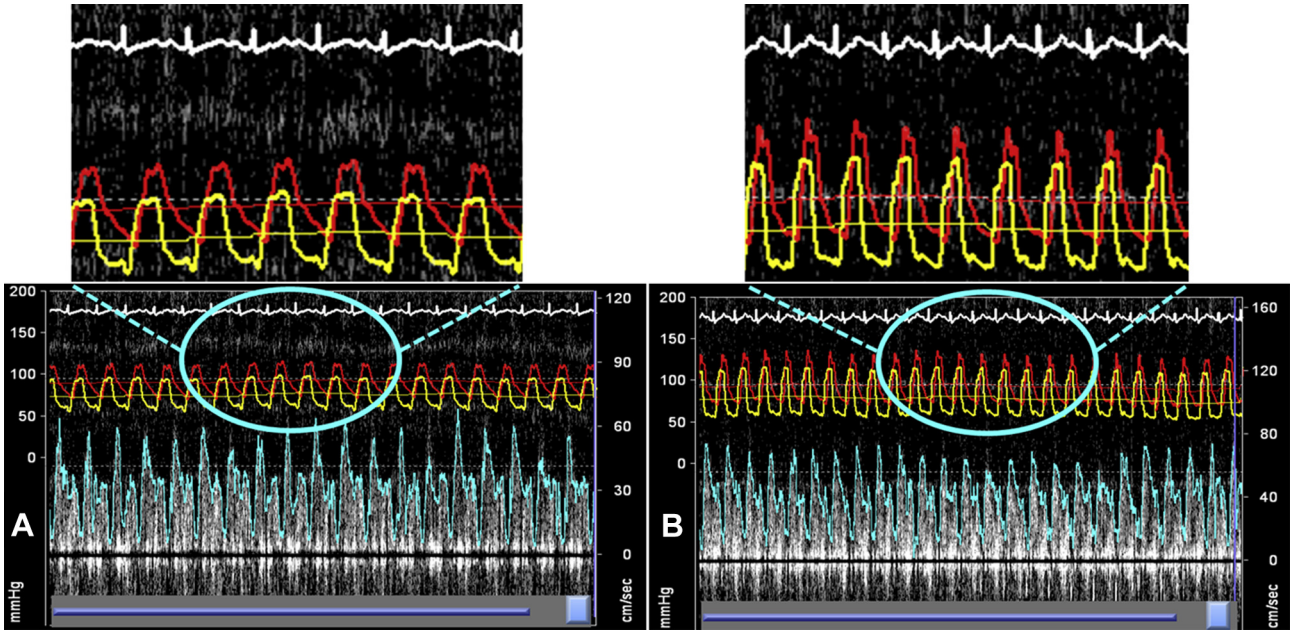

Figure 7 Intracoronary Hemodynamics From a Patient With Myocardial Bridging

Coronary blood velocity **(blue tracing)**, proximal pressure (Pa) **(red tracing)**, and distal pressure (Pd) **(yellow tracing)** measurements from a patient with myocardial bridging. **Blue circles** indicate the portions of the tracings magnified above each circle. **(A)** Adenosine (140 $\mu g \cdot kg^{-1} \cdot min^{-1}$): FFR = 0.83, APV = 28 cm/s; HR = 96 beats/min. **(B)** Dobutamine (60 $\mu g \cdot kg^{-1} \cdot min^{-1}$): FFR = 0.82, APV = 38 cm/s, HR = 122 beats/min. APV = average peak blood velocity; FFR = fractional flow reserve; HR = heart rate.

Table 2 Schwarz Classification for Myocardial Bridges and Treatment

Schwarz Type	Criteria	Objective Signs of Ischemia	Treatment
A	Incidental finding on angiography	−	None
B	Ischemia on stress test	+	BB or CCB
C	Altered intracoronary hemodynamics (quantitative coronary angiography/coronary flow reserve/Doppler)	+/−	BB or CCB and/or revascularization

BB = beta-blocker; CCB = calcium channel blocker.

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 "fingertip" phenomenon (Fig. 6). The abrupt acceleration in velocity 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. A rapid deceleration in velocity ensues as the bridge muscle relaxes and the cross-sectional area of the lumen increases. The velocity plateaus 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 nonbridged patients, there is a gray zone of ischemia with an FFR of 0.75 to 0.80. For a patient with an abnormal but nonischemic FFR (>0.80), intravenous administration of dobutamine can lead to higher pressure gradients (and sometimes ventricularization of the distal pressure tracing) and reproduction of angina symptoms, which would then suggest a clinically significant myocardial bridge (39). Higher average peak velocity and greater pressure gradients with infusion of dobutamine compared with adenosine suggest a hemodynamically significant myocardial bridge (Fig. 7A and B). 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 because it has been linked to clinical outcomes after pharmacological and invasive interventions (40). Patients with Schwarz type A need no treatment, whereas patients with types B and C show significant symptomatic improvement with beta-blockers or calcium channel blockers at 5-year follow-up. Patients with Schwarz type C refractory to medical therapy may be considered for revascularization of the myocardial bridge.

Management

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

Pharmacological therapy. Aggressive risk factor modification is advocated and antiplatelet therapy should be considered in patients with myocardial bridging because they are at increased risk for developing atherosclerosis. One approach to individualizing the need for antiplatelet therapy would be to perform MSCT to identify subclinical atherosclerosis. For symptomatic patients, beta-blockers remain the mainstay of treatment and relieve the hemodynamic disturbance caused by the myocardial bridge by decreasing the heart rate, increasing the 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 pharmacological effects of beta-blockers, may have vasodilatory effects that might be beneficial in

Table 3 Studies of Percutaneous Coronary Intervention for Myocardial Bridging

First Author, Year (Ref. #)	Study Cohort	Intervention	Follow-Up Period	Results
Klues et al., 1997 (42)	MB (n = 3)	BMS	7 weeks	No ISR or MACE
Haager et al., 2000 (45)	MB (n = 11)	BMS	2 yrs	45% ISR (7 weeks)
Kursaklioglu et al., 2004 (46)	MB (n = 12) Non-MB (n = 39)	BMS	6 months	ISR 67% in MB vs. 28% in non-MB
Kunamneni et al., 2008 (47)	MB (n = 12)	4 BMS 8 DES	1 yr	ISR 75% in BMS vs. 25% in DES
Tsujita et al., 2009 (48)	MB (n = 70) 34% of stents covering MB 66% of stents not covering MB	4 BMS 66 DES	1 yr	MB stent group: 33% MACE Non-MB stent group: 11% MACE
Ernst et al., 2013 (43)	MB (n = 15)	DES	5 yrs	1 perforation during stent implantation 19% ISR (6 months)

BMS = bare-metal stent(s); DES = drug-eluting stent(s); ISR = in-stent restenosis; MACE = major adverse cardiac events; MB = myocardial bridge.

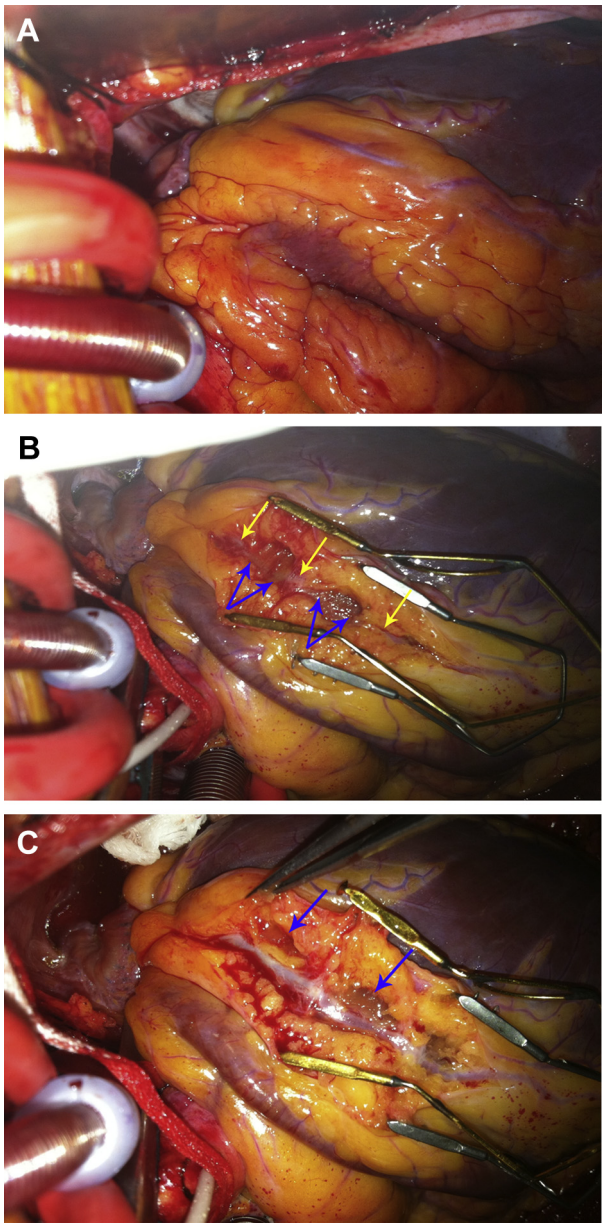

Figure 8 **Myotomy Procedure**

(A) View before incision showing the intramyocardial LAD. **(B)** Fat incised, showing the LAD **(yellow arrows)** and the bridging muscle **(blue arrows)**. **(C)** Unroofed LAD with cut ends of bridging muscle **(blue arrows)**. Abbreviation as in Figure 1.

patients with concomitant vasospasm. Head-to-head comparisons of beta-blockers and calcium channel blockers or randomized clinical trials of outcome benefits of beta-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 pre-load, they can worsen symptoms by intensifying systolic compression of the bridged segment and vasodilating segments proximal to the bridge (Fig. 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 coexisting coronary vasospasm.

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 2 conclusions: 1) stent implantation in patients with symptomatic myocardial bridges results in high rates of early in-stent restenosis that may be related to bridge-associated decreased lumen area; and 2) compared with PCI with bare-metal stents (BMS), PCI with drug-eluting stents (DES) has lower rates of target vessel revascularization (TVR).

Higher rates of restenosis were shown in patients undergoing PCI with BMS for symptomatic isolated myocardial bridging in one prospective study of 11 patients that reported early in-stent restenosis requiring TVR in 4 patients (45) and in another investigation comparing a similar cohort of 12 patients with 39 patients who underwent implantation of BMS for atherosclerotic lesions in the LAD (46). Although implantation of DES results in lower TVR rates than implantation of BMS, restenosis still occurs more frequently with PCI for symptomatic myocardial bridging than with PCI for atherosclerotic lesions. A small study that compared implantation of DES (n = 8) with BMS (n = 4) in symptomatic patients refractory to maximal medical therapy reported lower TVR rates in the DES group than in the BMS group, but both groups had higher rates than historical controls (47). Another investigation evaluated PCI with predominantly DES in 70 patients with both myocardial bridges and LAD lesions and divided them into 2 cohorts depending 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 with patients with stents ending proximal to the myocardial bridge (29% vs. 3%) (48). Interestingly, the 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 of 15 patients requiring revascularization within 6 months post-procedure but no further complications (43).

Any rationale for PCI in selected patients with a myocardial bridge would be to treat plaque proximal to the bridge as well as the negative remodeling and dynamic obstruction within the bridged segment. Although

Table 4 Studies of Surgical Interventions for Myocardial Bridging

First Author, Year (Ref. #)	Study Design	Procedure	Follow-Up Period	Immediate Post-Operative Results	Follow-Up Results
Iversen et al., 1992 (50)	Retrospective 9 patients	Myotomy	In-hospital	2 patients with right ventricular perforation All patients survived operation Post-operative studies showed flow restoration	None
Rezayat et al., 2006 (51)	Retrospective 26 patients	Myotomy	7–81 months (mean 34.2 months)	1 patient had post-operative angina with angiography showing narrowing in the left anterior descending coronary artery and subsequently underwent CABG with LIMA graft	2 patients with angina were treated medically No MACE
Wan and Wu, 2005 (54)	Retrospective 19 patients	4 PCI with BMS 8 CABG 7 myotomy	6–75 months (mean 23.5 months)	No complications	2 of 4 patients who underwent PCI had ISR; one subsequently underwent CABG No MACE in the surgical groups
Wu and Xu, 2007 (4)	Retrospective 31 patients	16 CABG 15 myotomy	3–115 months (mean 31 months)	1 patient with right ventricular perforation was successfully converted to CABG	21 of 31 patients (11 CABG, 10 myotomy) underwent follow-up angiography showing restoration of flow No MACE
Huang et al., 2007 (55)	Retrospective 11 patients Isolated myocardial bridge	8 CABG with LIMA graft 3 myotomy	6–120 months (median 35.3 months)	1 patient with right ventricular perforation was successfully converted to CABG	2 patients experienced atypical chest pain and were treated medically No MACE
Sun et al., 2012 (52)	Retrospective 13 patients Isolated myocardial bridge	CABG with LIMA graft	24–55 months	No complications	Patients were Canadian Cardiovascular Society class 0 or 1 7 patients underwent cardiac computed tomography angiography at 1 yr, no stenoses No MACE
Bockeria et al., 2013 (53)	Retrospective 39 patients Isolated myocardial bridge	CABG 19 with SVG 20 with LIMA graft	LIMA graft: 6–23 months SVG: 2–25 months	2 patients underwent repeat sternotomy for bleeding 2 patients required inotropes	6 of 39 patients had recurrent angina Angiography at 12 months showed occlusions in 12 LIMA grafts and 3 SVGs No mortality

CABG = coronary artery bypass grafting; LIMA = left internal mammary artery; PCI = percutaneous coronary intervention; SVG = saphenous vein graft; other abbreviations as in Table 3.

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 remains 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-by-case basis for symptomatic patients refractory to maximal medical therapy and who are not optimal surgical candidates.

Surgical treatment. Surgical intervention involves either supra-arterial myotomy or CABG. In a typical myotomy case (Fig. 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 regard 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 of myotomy described overall successful operations; however, 1 series reported accidental right ventricular wall perforation in 2 of 9 patients (50), and the other study reported that 1 of 26 patients underwent CABG for post-operative angina with LAD narrowing (51). Regarding CABG, one investigation reported no complications (52) and the second described 6 of 39 patients with recurrent angina and 15 of 39 patients with

graft occlusions on follow-up (53). Grafting with the left internal mammary artery was more likely to result in occlusion compared with grafting with the saphenous vein (12 vs. 3 patients), leading the investigators to conclude that grafting with the saphenous vein was preferable. This is in contrast to a previous report recommending the left internal mammary artery as the preferred graft for CABG (4).

Investigations comparing the effectiveness between myotomy and CABG in patients with symptomatic myocardial bridges consist of 1 study of 31 patients (4,54) and an even smaller series of 11 patients (55). In the first investigation, 1 myotomy case was converted to CABG after accidental right ventricular wall perforation. Twenty-one of 31 patients (either myotomy or CABG) who underwent follow-up angiography had restoration of distal coronary blood flow (4). In the second study, 2 of 11 patients experienced atypical chest pain and were managed medically (55).

Although 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, ≥75% 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 with surgical intervention. These limited data suggest that surgical therapy, either myotomy or CABG, appears safe and effective in symptomatic patients with myocardial bridging refractory to medical therapy.

Conclusions

Patients with myocardial bridging are commonly encountered clinically and may present with exertional symptoms of myocardial ischemia, syncope, and even sudden death. An array of noninvasive and invasive diagnostic modalities that have shed light on the pathophysiology of myocardial bridging can be deployed to evaluate symptomatic patients. Medical therapy with beta-blockers and calcium channel blockers remain the mainstay of 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.

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REFERENCES

1. Mohlenkamp S, Hort W, Ge J, Erbel R. Update on myocardial bridging. Circulation 2002;106:2616–22.
2. Bourassa MG, Butnaru A, Lesperance J, Tardif JC. Symptomatic myocardial bridges: overview of ischemic mechanisms and current diagnostic and treatment strategies. J Am Coll Cardiol 2003;41:351–9.
3. Alegria JR, Herrmann J, Holmes DR Jr., Lerman A, Rihal CS. Myocardial bridging. Eur Heart J 2005;26:1159–68.
4. Wu QY, Xu ZH. Surgical treatment of myocardial bridging: report of 31 cases. Chin Med J (Engl) 2007;120:1689–93.
5. Loukas M, Curry B, Bowers M, et al. The relationship of myocardial bridges to coronary artery dominance in the adult human heart. J Anat 2006;209:43–50.
6. Qian JY, Zhang F, Dong M, et al. Prevalence and characteristics of myocardial bridging in coronary angiogram—data from consecutive 5525 patients. Chin Med J (Engl) 2009;122:632–5.
7. Ferreira AG Jr., Trotter SE, Konig B Jr., Decourt LV, Fox K, Olsen EG. Myocardial bridges: morphological and functional aspects. Br Heart J 1991;66:364–7.
8. Attaran S, Moscarelli M, Athanasiou T, Anderson J. Is coronary artery bypass grafting an acceptable alternative to myotomy for the treatment of myocardial bridging? Interact Cardiovasc Thorac Surg 2013;16:347–9.
9. Ge J, Jeremias A, Rupp A, et al. New signs characteristic of myocardial bridging demonstrated by intracoronary ultrasound and Doppler. Eur Heart J 1999;20:1707–16.
10. Ishikawa Y, Akasaka Y, Suzuki K, et al. Anatomic properties of myocardial bridge predisposing to myocardial infarction. Circulation 2009;120:376–83.
11. Cheng C, Tempel D, van Haperen R, et al. Atherosclerotic lesion size and vulnerability are determined by patterns of fluid shear stress. Circulation 2006;113:2744–53.
12. Malek AM, Alper SL, Izumo S. Hemodynamic shear stress and its role in atherosclerosis. JAMA 1999;282:2035–42.
13. Walpola PL, Gotlieb AI, Cybulsky MI, Langille BL. Expression of ICAM-1 and VCAM-1 and monocyte adherence in arteries exposed to altered shear stress. Arterioscler Thromb Vasc Biol 1995;15:2–10.
14. McNally JS, Davis ME, Giddens DP, et al. Role of xanthine oxidoreductase and NAD(P)H oxidase in endothelial superoxide production in response to oscillatory shear stress. Am J Physiol Heart Circ Physiol 2003;285:H2290–7.
15. Ishii T, Asuwa N, Masuda S, Ishikawa Y, Kiguchi H, Shimada K. Atherosclerosis suppression in the left anterior descending coronary artery by the presence of a myocardial bridge: an ultrastructural study. Mod Pathol 1991;4:424–31.
16. Samady H, Eshtehardi P, McDaniel MC, et al. Coronary artery wall shear stress is associated with progression and transformation of atherosclerotic plaque and arterial remodeling in patients with coronary artery disease. Circulation 2011;124:779–88.
17. Herrmann J, Higano ST, Lenon RJ, Rihal CS, Lerman A. Myocardial bridging is associated with alteration in coronary vasoreactivity. Eur Heart J 2004;25:2134–42.
18. Ge J, Erbel R, Gorge G, Haude M, Meyer J. High wall shear stress proximal to myocardial bridging and atherosclerosis: intracoronary ultrasound and pressure measurements. Br Heart J 1995;73:462–5.
19. Humphrey JD. Vascular adaptation and mechanical homeostasis at tissue, cellular, and sub-cellular levels. Cell Biochem Biophys 2008;50:53–78.

20. Verhagen SN, Rutten A, Meijs MF, et al. Relationship between myocardial bridges and reduced coronary atherosclerosis in patients with angina pectoris. Int J Cardiol 2013;167:883–8.
21. Berry JF, von Mering GO, Schmalfuss C, Hill JA, Kerensky RA. Systolic compression of the left anterior descending coronary artery: a case series, review of the literature, and therapeutic options including stenting. Catheter Cardiovasc Interv 2002;56:58–63.
22. Gowda RM, Khan IA, Ansari AW, Cohen RA. Acute ST segment elevation myocardial infarction from myocardial bridging of left anterior descending coronary artery. Int J Cardiol 2003;90:117–8.
23. Tio RA, Ebels T. Ventricular septal rupture caused by myocardial bridging. Ann Thorac Surg 2001;72:1369–70.
24. Ural E, Bildirici U, Celikyurt U, et al. Long-term prognosis of non-interventionally followed patients with isolated myocardial bridge and severe systolic compression of the left anterior descending coronary artery. Clin Cardiol 2009;32:454–7.
25. Kodama K, Morioka N, Hara Y, Shigematsu Y, Hamada M, Hiwada K. Coronary vasospasm at the site of myocardial bridge—report of two cases. Angiology 1998;49:659–63.
26. Feld H, Guadanino V, Hollander G, Greengart A, Lichstein E, Shani J. Exercise-induced ventricular tachycardia in association with a myocardial bridge. Chest 1991;99:1295–6.
27. Kracoff OH, Ovsyshcher I, Gueron M. Malignant course of a benign anomaly: myocardial bridging. Chest 1987;92:1113–5.
28. den Dulk K, Brugada P, Braat S, Heddle B, Wellens HJ. Myocardial bridging as a cause of paroxysmal atrioventricular block. J Am Coll Cardiol 1983;1:965–9.
29. Marchionni N, Chechi T, Falai M, Margheri M, Fumagalli S. Myocardial stunning associated with a myocardial bridge. Int J Cardiol 2002;82:65–7.
30. Roul G, Sens P, Germain P, Bareiss P. Myocardial bridging as a cause of acute transient left heart dysfunction. Chest 1999;116:574–80.
31. Tio RA, Van Gelder IC, Boonstra PW, Crijns HJ. Myocardial bridging in a survivor of sudden cardiac near-death: role of intracoronary doppler flow measurements and angiography during dobutamine stress in the clinical evaluation. Heart 1997;77:280–2.
32. Morales AR, Romanelli R, Boucek RJ. The mural left anterior descending coronary artery, strenuous exercise and sudden death. Circulation 1980;62:230–7.
33. Kim PJ, Hur G, Kim SY, et al. Frequency of myocardial bridges and dynamic compression of epicardial coronary arteries: a comparison between computed tomography and invasive coronary angiography. Circulation 2009;119:1408–16.
34. Gawor R, Kusmierek J, Plachcinska A, et al. Myocardial perfusion GSPECT imaging in patients with myocardial bridging. J Nucl Cardiol 2011;18:1059–65.
35. Galbraith EM, Eshtehardi P, Samady H. SPECT perfusion imaging and myocardial bridges: bridging the gap of diagnostic uncertainty. J Nucl Cardiol 2011;18:1000–2.
36. Gaibazzi N, Rigo F, Reverberi C. Severe coronary tortuosity or myocardial bridging in patients with chest pain, normal coronary arteries, and reversible myocardial perfusion defects. Am J Cardiol 2011;108:973–8.
37. Hongo Y, Tada H, Ito K, Yasumura Y, Miyatake K, Yamagishi M. Augmentation of vessel squeezing at coronary-myocardial bridge by nitroglycerin: study by quantitative coronary angiography and intravascular ultrasound. Am Heart J 1999;138:345–50.
38. Kern MJ, Samady H. Current concepts of integrated coronary physiology in the catheterization laboratory. J Am Coll Cardiol 2010;55:173–85.
39. Escaned J, Cortes J, Flores A, et al. Importance of diastolic fractional flow reserve and dobutamine challenge in physiologic assessment of myocardial bridging. J Am Coll Cardiol 2003;42:226–33.
40. Schwarz ER, Gupta R, Haager PK, et al. Myocardial bridging in absence of coronary artery disease: proposal of a new classification based on clinical-angiographic data and long-term follow-up. Cardiology 2009;112:13–21.
41. Schwarz ER, Klues HG, vom Dahl J, Klein I, Krebs W, Hanrath P. Functional, angiographic and intracoronary Doppler flow characteristics in symptomatic patients with myocardial bridging: effect of short-term intravenous beta-blocker medication. J Am Coll Cardiol 1996;27:1637–45.
42. Klues HG, Schwarz ER, vom Dahl J, et al. Disturbed intracoronary hemodynamics in myocardial bridging: early normalization by intracoronary stent placement. Circulation 1997;96:2905–13.
43. Ernst A, Bulum J, Separovic Hanzevacki J, Lovric Bencic M, Strozzi M. Five-year angiographic and clinical follow-up of patients with drug-eluting stent implantation for symptomatic myocardial bridging in absence of coronary atherosclerotic disease. J Invasive Cardiol 2013;25:586–92.
44. Tandar A, Whisenant BK, Michaels AD. Stent fracture following stenting of a myocardial bridge: report of two cases. Catheter Cardiovasc Interv 2008;71:191–6.
45. Haager PK, Schwarz ER, vom Dahl J, Klues HG, Reffelmann T, Hanrath P. Long term angiographic and clinical follow up in patients with stent implantation for symptomatic myocardial bridging. Heart 2000;84:403–8.
46. Kursaklioglu H, Barcin C, Iyisoy A, Kose S, Amasyali B, Isik E. Angiographic restenosis after myocardial bridge stenting. Jpn Heart J 2004;45:581–9.
47. Kunamneni PB, Rajdev S, Krishnan P, et al. Outcome of intracoronary stenting after failed maximal medical therapy in patients with symptomatic myocardial bridge. Catheter Cardiovasc Interv 2008;71:185–90.
48. Tsujita K, Maehara A, Mintz GS, et al. Impact of myocardial bridge on clinical outcome after coronary stent placement. Am J Cardiol 2009;103:1344–8.
49. Derkacz A, Nowicki P, Protasiewicz M, Reczuch K, Szczepanik-Osadnik H, Witkowska M. [Multiple percutaneous coronary stent implantation due to myocardial bridging—a case report]. Kardiol Pol 2007;65:684–7.
50. Iversen S, Hake U, Mayer E, Erbel R, Diefenbach C, Oelert H. Surgical treatment of myocardial bridging causing coronary artery obstruction. Scand J Thorac Cardiovasc Surg 1992;26:107–11.
51. Rezayat P, Hassan D, Amirreza S, Susan H. Myocardial bridge. Surgical outcome and midterm follow up. Saudi Med J 2006;27:1530–3.
52. Sun X, Chen H, Xia L, Zhao D, Ding W, Wang C. Coronary artery bypass grafting for myocardial bridges of the left anterior descending artery. J Card Surg 2012;27:405–7.
53. Bockeria LA, Sukhanov SG, Orekhova EN, Shatakhyan MP, Korotayev DA, Sternik L. Results of coronary artery bypass grafting in myocardial bridging of left anterior descending artery. J Card Surg 2013;28:218–21.
54. Wan L, Wu Q. Myocardial bridge, surgery or stenting? Interact Cardiovasc Thorac Surg 2005;4:517–20.
55. Huang XH, Wang SY, Xu JP, et al. Surgical outcome and clinical follow-up in patients with symptomatic myocardial bridging. Chin Med J (Engl) 2007;120:1563–6.

Key Words: coronary wall shear stress ■ intracoronary Doppler velocity and pressure ■ intravascular imaging ■ myocardial bridge ■ myotomy ■ percutaneous coronary intervention.