Temporal Changes in Interpapillary Muscle Dynamics as an Active Indicator of Mitral Valve and Left Ventricular Interaction in Ischemic Mitral Regurgitation

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ABSTRACT

BACKGROUND Regional subpapillary myocardial hypokinesis may impair lateral reduction in the interpapillary muscle distance (IPMD) from diastole to systole, and adversely affect mitral valve geometry and tethering.

OBJECTIVES The goal of this study was to investigate the impact of impaired lateral shortening in the interpapillary muscle distance on mitral valve geometry and function in ischemic heart disease.

METHODS To quantify ventricular size/shape, regional myocardial contraction, lateral shortening of the IPMD, mitral valve geometry, and severity of mitral regurgitation, 67 patients with ischemic heart disease underwent cardiac magnetic resonance imaging, and a correlation analysis of measured parameters was performed. The impact of reduced IPMD shortening on mitral valve (dys)function was confirmed in swine and in a physiological computational mitral valve model.

RESULTS Lateral shortening of the IPMD from diastole to systole was severely reduced in patients with moderate/severe ischemic mitral regurgitation (9.6 ± 2.8 mm), but preserved in mild IMR (11.5 ± 3.4 mm). Left ventricular size and ejection fraction did not differ between the groups. In swine with subpapillary infarction and impaired IPMD, mitral regurgitation was evident within 1 week, compared to those pigs with a nonpapillary infarction and preserved IPMD. In the controlled computational valve model, IPMD had the maximal impact on regurgitation, and was exacerbated with additional annular dilation.

CONCLUSIONS By using cardiac magnetic resonance imaging in humans, we demonstrated that it is the impairment of lateral shortening between the papillary muscles, and not passive ventricular size, that governs the severity of mitral regurgitation. Loss of lateral shortening of IPMD tethers the leaflet edges and impairs their systolic closure, resulting in mitral regurgitation, even in small ventricles. Understanding the lateral dynamics of ventricular-valve interactions could aid the development of new repair techniques for ischemic mitral regurgitation. (J Am Coll Cardiol 2014;64:1867–79)

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Ischemic mitral regurgitation (IMR) is a common lesion of the mitral valve (MV), which develops secondary to acute myocardial infarction or chronic ischemia of the left ventricle (LV) (1). Animal studies suggest that post-infarction LV dilation and subsequent systolic leaflet tethering are implicated in the development of IMR (2,3). However, in the clinical setting, often patients present with significant IMR with small ventricles and sometimes with minimal IMR even with severely dilated ventricles (4,5). This divergence between LV size and IMR may be due to differences in regional myocardial radial contractility that alter valve dynamics, irrespective of the ventricular size. During systole, radial contraction of the LV translates to MV closure via increased transmitral pressure, annular contraction, and lateral shortening of the interpapillary muscle distance (IPMD) (6-8). Diastolic to systolic shortening of the IPMD induces slackness in the marginal and secondary chordae during systolic closure and allows basal leaflet motion toward coaptation, as shown in Figures 1A and 1B. Loss of systolic shortening of IPMD due to regional subpapillary scarring/hypokinesis of the myocardial wall can alter the MV force balance and restrict its coaptation.

We hypothesize that in patients with IMR, it is not the passive LV size but the loss of lateral IPMD shortening that governs IMR severity. Perturbed or reduced IPMD shortening may stretch the free edges of the leaflets and restrict their deformation for coaptation, irrespective of LV size. In this study, we tested this hypothesis in 3 stages: 1) used late gadolinium-enhanced cardiac magnetic resonance imaging to quantitatively relate ventricular scarring and wall hypokinesis/dyskinesis to IPMD shortening and IMR severity; 2) validated the hypothesis in a controlled swine model of myocardial infarction; and 3) demonstrated the isolated impact of IPMD shortening loss and LV size on valve biomechanics using a computational valve model.

METHODS

PATIENT SELECTION. Sixty-seven patients with ischemic heart disease confirmed by cardiac catheterization underwent cardiac magnetic resonance imaging at Emory University, with institutional review board approval to access patient data and history (IRB #00046322). Stenosis $\geq 50\%$ in $\geq 1$ coronary vessels, previous myocardial infarction, and history of coronary revascularization were used as inclusion criteria. Those with any MV structural deterioration from degenerative or rheumatic disease, ventricular aneurysms, Dor procedures, and pericardial effusions that impaired image segmentation were excluded. Ventricular aneurysms were defined as large, thinned myocardial bulging identified on short-axis images of the LV 1 patient with severe pericardial effusion that impaired clear delineation of the epicardial border of the LV for segmentation was excluded. Thirteen of these patients had a history of atrial fibrillation, and data analysis was performed with and without their inclusion in this study.

CARDIAC MAGNETIC RESONANCE IMAGING. Imaging was performed with a Philips Intera 1.5-T system (Philips Healthcare, Andover, Massachusetts), with a breath-hold, electrocardiogram-gated protocol. Cine sequences were acquired in 2- and 4-chamber horizontal long-axis views with a repetition time/echo time of 3.0/1.5 ms, respectively, a flip angle of $65^\circ$, slice thickness of 8 mm, and an in-plane resolution of $1.4 \times 1.4$ mm$^2$. A short-axis stack of 8 to 10, slices, each 10 mm thick, were obtained from the LV base through the apex over 20 cardiac phases (Figure 1C) to delineate the wall motion. The end-diastolic frame and end-systolic frame were identified and used to calculate IPMD shortening and fractional shortening, whereas all 20 phases are reported only in the temporal graphs. Free-breathing, electrocardiogram-triggered, velocity-encoded magnitude and phase images were obtained at the level of the pulmonary artery bifurcation to compute aortic outflow. IMR fraction (IMRF) was computed by dividing the regurgitant flow (stroke volume – forward aortic flow) by the stroke volume, and patients were divided into a mild IMR group (IMRF $<30\%$) and a moderate/severe group (IMRF $\geq 30\%$), per clinical guidelines.

MYOCARDIAL SEGMENTATION AND THICKENING ANALYSIS. Semiautomated segmentation of the endocardial and epicardial borders was performed in each short-axis slice, excluding the papillary muscles (PMs), through all the cardiac phases. Radial LV wall thickening was used as an index of regional myocardial contractility and motion and reported using a 4-segment LV model (segment 1, septum spanning between the 2 right ventricular [RV] insertion points into the LV; segment 2, region between the anterior right ventricular insertion and the anterolateral PM; segment 3, region between the anterolateral and posteromedial PMs; and segment 4, region between the posteromedial PM and the inferior right ventricular insertion), demonstrated in Figures 1D and 1E. In the basal slices in which multiple PM tips
were visible, all anterior PM heads were included in sector 2 and all posterior PM heads in sector 3. Three-dimensional LV volumes were reconstructed as shown in Figure 1F, and total and forward ejection fractions (EF) were computed.

**REGIONAL SCAR ANALYSIS.** Scar quantification was performed in 45 patients, with the location and extent of scar measured from gadolinium-hyperenhanced phase-sensitive inversion recovery images. Twenty-two patients with impaired renal function could not undergo gadolinium-enhanced imaging. Otsu’s method was used to automatically delineate the scar, and the transmurality was assessed using the scar transmurality area-based method (9–11). Briefly, Otsu’s method delineates hyperenhanced brighter regions of the left ventricle with a level set segmentation method. The scar transmurality area-based method is an averaging technique whereby the scar area in a ventricular segment is normalized by the total segment area and reported as the scar transmurality percentage (12,13).

**IPMD AND MV GEOMETRY.** Diastolic IPMD and IPMD shortening and fractional shortening from diastole to systole were measured in the short-axis slice where the bodies of the 2 PMs were evident (Figure 2). Measurements were obtained in a plane passing through the bodies of the 2 muscles and not their tips, to avoid measurement discrepancies from multihed PMs. Segment 1.9 (MedViso Inc., Lund, Sweden)
Sweden) corrects for long-axis motion by autodetecting valve plane motion, improving the accuracy of the measurements (44). Temporal changes in this distance through the cardiac cycle and absolute and proportional changes between end-diastolic and end-systolic frames are reported. The systolic tenting area was measured in a 2-chamber long-axis view, as reported in published studies (15–17), and the distance from the PM tips to the anterior and posterior mitral annulus was measured in the same view in those patients with visible PM heads (n = 57).

**SUBPAPILLARY VERSUS NONPAPILLARY INFACTION IN SWINE.** In swine, an equatorial infarction was induced with percutaneous ethanol injection in selected obtuse marginal (OM) branches of the left circumflex artery. Simultaneous left ventriculography and angiography were performed with the camera in left anterior oblique position, angled at 55° to 60°, to identify the perfusion patterns of the left circumflex artery to the posterior ventricular wall, as shown in Figures 3A to 3C. OM2/3 occlusion resulted in a subpapillary infarction beneath the posteromedial PM (IPMD shortening severely reduced) and OM1/2 occlusion resulted in a nonpapillary infarction beside, but not involving, the posteromedial PM (IPMD preserved) was induced in 3 swine each, as shown in Figures 3D and 3E. Image-guided occlusion of targeted vessels enabled reproducible infarct sizes and locations as desired in these animals. The animals were survived to 1 week and underwent echocardiography at baseline, post-infarction, and 1 week.

**COMPUTATIONAL MODELING OF THE MV.** A realistic, anatomically accurate MV computational model was used to assess the impact of IPMD with/without LV dilation on MV function and leaflet and chordal stresses (18,19). MV anatomy was reconstructed from computed tomography images of a heart; a geometric mesh was generated with Hypermesh (Altair Engineering Inc., Troy, Michigan) with 8-node hexahedral C3D8I, 6-node pentahedral C3D6 elements, and 3-dimensional truss chordal elements. An anisotropic, fiber-reinforced hyperelastic material model was used to model the leaflet mechanical properties, and an isotropic hyperelastic Ogden material model

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**FIGURE 3** Animal Model in Which Lateral Shortening of the Interpapillary Muscle Shortening Can be Controlled

(A to C) Fluoroscopic images depicting the steps to identify the papillary muscle in the ventricle in relation to the obtuse marginal (OM) branches of the left circumflex artery. (D1, D2) Infarction of posterior mitral annulus, posterior papillary muscle, and posterolateral wall after occlusion of OM2/3 branches depicted using tetrazolium stain. (D3) Moderate mitral regurgitation seen on echocardiography after OM2/3 occlusion. (E1, E2) Infarction of the nonpapillary posterolateral wall alone after occlusion of the OM1 branch. (E3) Absence of mitral regurgitation after occlusion of the OM1 branch. EtOH = ethanol.
was used for the chordae tendineae. Annular and PM dynamics and location were applied as kinematic boundary conditions, and time-resolved physiological transmural pressure was applied on the ventricular surface of the leaflets. A dynamics-explicit analysis was performed to mimic valve closure, and the changes in the regurgitant orifice area were computed. Multiple simulations were performed with a variety of geometric perturbations: Sim 1, baseline; Sim 2, loss of lateral shortening of IPMD (normal annulus and LV size); Sim 3, LV dilation with 7-mm apical-lateral PM displacement (normal annulus and LV); Sim 4, loss of lateral shortening of IPMD + LV dilation (normal annulus); Sim 5, loss of lateral shortening of IPMD + dilated annulus (normal LV); Sim 6, LV dilation + dilated annulus (normal IPMD shortening); and Sim 7, LV dilation + dilated annulus + loss of lateral IPMD shortening.

**Statistical Analysis.** Anderson-Darling test for normality was used and data reported as mean ± SD. The unpaired Student t or Fisher exact test was used for comparison of groups. The Pearson correlation test was used for correlation between parameters. A paired Student t test was used for paired measurements of the mitral regurgitation index in swine, whereas an unpaired Student t test was used to compare volumes between different groups of swine. Multiple linear regressions were performed to analyze the interactive impact of myocardial scar, wall thickening, and global EF on IPMD (fractional) shortening. A p value <0.05 was considered significant in all the statistical analyses.

**Results**

**Patient Demographic Data.** Patient characteristics and cardiac comorbidities are reported in Table 1 for the 2 groups of patients with mild (n = 26) and moderate/severe (n = 41) IMR. IMRF significantly differed between the 2 groups, with a mean of 17.5 ± 6.4% in mild IMR and 46.6 ± 9.2% in moderate/severe IMR patients (p < 0.0001). The mean age of the entire population was 65.2 ± 10.3 years, with no differences between patients with mild and moderate/severe IMR (p = 0.09). No significant differences were noted in the clinical history of the groups.

**LV Function and Structure.** The 2 groups had comparable EF, with 51.8 ± 17.4% in the mild IMR group and 46.3 ± 20.6% in the moderate/severe IMR group (p = 0.26). However, forward EF was significantly lower in the moderate/severe IMR group (p < 0.0001) (Table 2). End-diastolic ventricular volume indicative of maladaptive ventricular dilation, peak thickening, anterolateral wall, mm 6.0 ± 3.3 in mild/mild MR and 4.7 ± 2.8 in moderate/severe MR (p < 0.0001).
end-diastolic volume indicative of contractile dysfunction, and LV sphericity index did not differ between the 2 groups, as outlined in Table 2.

**REGIONAL SCAR ASSESSMENT.** In the 45 patients, scar transmurality in equatorial segment 3 positively correlated with IMRF ($r = 0.47$; $p = 0.001$) with a mean of $45.7 \pm 16.3\%$ in moderate/severe IMR ($n = 27$) compared with $29.3 \pm 17.7\%$ ($p = 0.002$) in mild IMR ($n = 18$), shown in Figure 4. Scar transmurality in this region also negatively correlated with peak wall thickening and IPMD absolute and fractional shortening.

**REGIONAL MYOCARDIAL CONTRACTILITY AND MITRAL REGURGITATION.** A significant reduction in the peak systolic wall thickening was observed only in the equatorial and apical ventricular segments, with significant reductions in segments 2 and 3 in patients with or without atrial fibrillation, as shown in Figure 5. In the equatorial region, peak diastolic-to-systolic wall thickening in segment 2 was less in the patients with moderate/severe IMR ($4.7 \pm 2.8$ mm) than in patients with mild IMR ($6.7 \pm 3.3$ mm; $p = 0.01$) by 28.8%, as shown in Figure 6A. Figure 6B shows a similar trend in segment 3 of the equatorial region, with the moderate/severe IMR group having reduced peak wall thickening of $4.1 \pm 2.8$ mm compared with $6.0 \pm 3.3$ mm ($p = 0.01$) in the mild IMR group. In the apical ventricular region, a parallel reduction was seen in segments 2 and 3 in the moderate/severe IMR group, as shown in Figures 6C and 6D. Peak thickening in these equatorial segments had a significant negative correlation with IMRF ($r = -0.47$, $p = 0.0002$ for segment 3), as shown in Figures 6E and 6F, indicating that reduced contraction in these segments directly affects MV function.

**IPMD SHORTENING AND MV FUNCTION.** Hypokinetic myocardial segments 2 and 3 in the equatorial region directly underlie the PMs, and loss of wall thickening or contraction in these segments can directly impair the lateral IPMD shortening. The end-diastolic IPMD was not different between the 2 groups ($p = 0.23$) (Figure 7A). However, Figures 7B and 7C show that in patients with mild IMR, the diastolic-to-systolic IPMD shortening was significantly greater at $11.5 \pm 3.4$ mm in mild IMR compared with $9.6 \pm 2.8$ mm in the moderate/severe IMR group ($p = 0.02$). Such IPMD absolute and fractional shortening had a significant positive
FIGURE 5 Regional Myocardial Wall Thickening and Ischemic MR

Graphs representing segment-wise regional myocardial wall thickening in basal, equatorial, and apical regions over 20 phases of the cardiac cycle: X-axis = cardiac phases; Y-axis = wall thickening (mm). Significant reduction in peak systolic thickening was seen in equatorial and apical segments 2 and 3. Mild MR (n = 26) (solid slate line), mild MR without atrial fibrillation (n = 19) (dotted slate line), moderate/severe MR (n = 41) (solid red line); moderate/severe MR (n = 35) (dotted red line). ED = end-diastole; ES = end-systole; MR = mitral regurgitation.

FIGURE 6 Correlation Between Regional Wall Thickening and Severity of MR

(A, B) Bar graphs showing significant reduction in peak thickening in equatorial segments 2 and 3. (C, D) Bar graphs showing reduction in peak thickening in apical segments 2 and 3. (E, F) Graphs representing significant negative correlation of peak thickening in equatorial segments 2 and 3 and MR fraction. Abbreviations as in Figure 4.
correlation with the underlying ventricular wall thickening and a significant negative correlation with IMRF ($r_{\text{IPMD}} = -0.26, p_{\text{IPMD}} = 0.03; r_{\text{FrIPMD}} = -0.32, p_{\text{FrIPMD}} = 0.008$), shown in Figures 7D to 7I. The end-systolic IPMD has a significant positive correlation with tenting area ($r = 0.437; p = 0.0002$), indicating a direct impact of this dimension on valve coaptation in Figure 7J. The systolic distance between the PM tip and the anterior and posterior annuli was not significantly different in the 2 patient groups, further demonstrating that ventricular size is not a well-defined correlate of IMR severity in these patients (Figures 7K and 7L). Multivariate analysis demonstrated that fractional IPMD shortening negatively correlates with scar transmurality in segment 3 ($r = -0.36; p = 0.01$) and positively correlates with peak thickening in
segment 3 ($r = 0.47; p < 0.0001$) and with global EF ($r = 0.59; p < 0.0001$).

**SUBPAPILLARY VERSUS NONPAPILLARY INFARCTION IN A SWINE MODEL.** In all of the swine with OM2/3 occlusion, moderate IMR of $30.4 \pm 9.3\%$ developed at 1 week ($p < 0.0001$ to baseline), whereas those with OM1 occlusion had trace IMR of $10.7 \pm 3.5\%$ ($p = 0.63$ to baseline), shown in Figures 3E and 3F. LV volumes were comparable between the groups at the end of the 1-week time period, with a biplane end-diastolic volume of $105 \pm 26.1\ ml$ in group 1 with mitral regurgitation and $114.9 \pm 6.5\ ml$ in group 2 without mitral regurgitation ($p = 0.63$) and an end-systolic volume of $70.5 \pm 23.9\ ml$ in group 1 and $64.6 \pm 2.8\ ml$ in group 2 ($p = 0.74$).

**MV REGURGITANT ORIFICE AREA IN A COMPUTATIONAL VALVE MODEL.** In the simulation, the baseline model did not have regurgitation, and the regurgitant orifices with varied annular and ventricular geometric perturbations are summarized in Table 3. Loss of IPMD shortening alone generated an orifice size of $41\ mm^2$, which increased with the addition of annular dilation to $88\ mm^2$ but did not differ further with the addition of LV dilation. LV dilation alone resulted in an orifice of $9\ mm^2$ only, which increased to $58\ mm^2$ with concomitant loss of IPMD, and was equivalent to a $61-mm^2$ orifice with the addition of annular dilation, but with lateral IPMD shortening preserved. Representative images of the regurgitant orifice area and anterior leaflet stress are shown in Figure 8.

**DISCUSSION**

The principal finding of this study is that loss of lateral IPMD shortening from diastole to systole...
positively correlates with higher severity of IMR, even when the LV volumes are comparable. This finding emphasizes that, in addition to the passive LV size, dynamic interaction between the LV and the MV is important in the pathogenesis of IMR. Infarction of the myocardium behind or beneath one or both the PMs, and loss of equatorial contraction of these regions and scarring, are factors that impair lateral IPMD shortening and correlate with greater IMR severity. In swine controlled for the location of infarction, IMR seemed to develop only in those animals with a subpapillary infarction compared with those without, even with comparable LV volumes. In the computational model, in which annular size, IPMD lateral shortening, and LV dilation were independent, the loss of IPMD shortening and its combination with annular dilation had the greatest adverse impact on valve function.

Anatomically, as shown in the Central Illustration, the MV leaflets that open and close with cyclic changes in the transmitral gradient are synchronized with LV contraction through the PMs. It is reasonable...
to hypothesize that, although the transmitral gradient enables basal motion of leaflets toward coaptation, the regional LV contractile dynamics and the orientation of the PMs in relation to the mitral annulus enable precise adjustments for leaflet coaptation from one commissure to another (20). Such precise adjustments would be necessary for leaflet coaptation, considering the anatomic mismatch in the anterior and posterior annular sections and the dimensions of the anterior and posterior leaflets. We demonstrate that the breakdown of these precision-adjustment systems in ischemic heart disease contributes to the development of IMR. Mechanistically, in a normal heart, lateral IPMD reduction in each cardiac cycle can reduce tension in the marginal chordae of the 2 leaflets in early systolic phases, enabling basal motion of the leaflets toward the mitral annulus into the coaptation, as described in the Central Illustration. With loss of lateral IPMD shortening, the marginal chordae remain taut through these early systolic phases, resulting in either leaflet mismatch or localized loss of coaptation, which, in turn, results in IMR. In this study, we not only demonstrate this mechanism linking regional LV contraction to MV function, but also validate anecdotal observations from other investigators. Flynn et al. (21) reported that patients with higher scar burden in the posterolateral wall often presented with severe MR after coronary revascularization, and Srichai et al. (5) demonstrated a correlation between localized ventricular fibrosis over LV size and IMR severity, but neither study could correlate these LV characteristics with MV function.

The results of our study deviate from those of previously published pre-clinical models in which IMR severity is solely attributed to LV size, although the clinical correlation between LV size and IMR is rather weak. The discrepancy between animal studies and this study in humans may be attributed to the acute nature of the infarction, leading to rapid LV dilation, whereas in most humans, coronary artery stenosis occurs gradually. In this period of gradual stenosis, regional myocardial dyskinesis can occur, and IMR may develop and can, in turn, induce LV remodeling and dilation. Thus, patients presenting in early stages of this process may not present with large ventricles yet may have significant IMR, whereas those in the later stages of this process may have enlarged ventricles with IMR (summarized in Figure 9). In addition, emerging evidence of biological changes in the MV leaflets in the early phases after an infarction indicate an additional role of MV adaptation in IMR pathogenesis. Altered mechanical stresses in the valve leaflets from breakdown of the precision-adjustment mechanisms after an infarction, and the inflammatory biochemical environment can cause early leaflet adaptation, fibrosis, and stiffening (22).

The results of this study have clinical implications in identifying patients at risk of the development of IMR after an infarction or those patients who may not have resolution of IMR after revascularization and require MV repair. Pre-operative echocardiography and cardiac magnetic resonance imaging are 2 imaging modalities that are sufficient to measure the lateral IPMD dynamics. If a subpapillary ischemic or

**FIGURE 9** A New Pathogenic Mechanism of IMR With Therapeutic Options

A new mechanism of MR focused on MV and LV dynamic interactions. CRT = cardiac resynchronization therapy; IMR = ischemic mitral regurgitation; TGF = transforming growth factor; TMVR = transcatheter mitral valve repair; other abbreviations as in Figure 1.
infarction zone is identified with reduced shortening of the IPMD, the patient may already have IMR or IMR may subsequently develop, and an appropriate clinical course of action may be determined. Similarly, if adequate restoration of regional myocardial kinesis in the subpapillary muscle region cannot be established after revascularization, the potential risk of IMR developing after intervention is higher. Although existing therapies for IMR focus largely on passive MV or LV structure, these findings point toward new treatment strategies. Increasing equatorial wall contraction and restoring IPMD lateral shortening via cardiac resynchronization therapy can be a simple treatment option. Ypenburg et al. (23) demonstrated in a patient cohort that increasing equatorial LV contraction reduced IMR after cardiac resynchronization therapy, although this study lacked detailed measurements of interpapillary muscle dynamics. Targeted stem cell therapy or gene therapy to improve equatorial wall contraction may also be beneficial. In the surgical setting, where LV contraction may be worse and the onset of LV dilation may already have occurred, use of a papillary muscle sling to reduce the interpapillary muscle distance or use of an external splint such as the Coapsys system (Myocor Inc., Maple Grove, Minnesota) to reduce the IPMD may be more beneficial than simple undersizing mitral annuloplasty.

**STUDY LIMITATIONS.** A limitation of this study relates to referral bias in that only patients presenting to the Division of Cardiothoracic Surgery at our institution with a history of ischemic heart disease were recruited. This patient population has had previous infarctions and coronary stents/surgical revascularization, and the association of these events to the origin of the MR is unknown. This does not hamper this study’s objective; regardless of the underlying cause, we demonstrated that preoperative loss of interpapillary muscle dynamics correlates with the development of IMR. MV remodeling could not be addressed in this patient cohort due to 2-dimensional magnetic resonance imaging and the lack of valve samples in these patients.

**CONCLUSIONS**

Loss of lateral interpapillary muscle shortening tethers the leaflet edges and impairs their systolic closure, resulting in mitral regurgitation, even in small ventricles. Understanding the lateral dynamics of ventricle-valve interactions could aid the development of new repair techniques for ischemic mitral regurgitation.

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**PERSPECTIVES**

**COMPETENCY IN MEDICAL KNOWLEDGE 1:** Three-dimensional echocardiography and multislice cardiac computed tomography can be used to assess changes in the distance between the papillary muscles during the cardiac cycle.

**COMPETENCY IN MEDICAL KNOWLEDGE 2:** The amount of systolic reduction in lateral separation between the papillary muscles is related to the severity of mitral regurgitation after myocardial infarction.

**TRANSLATIONAL OUTLOOK:** The effects of therapies, such as transapical banding that restore interpapillary muscle dynamics, on MV function and clinical outcomes warrant investigation.

**REFERENCES**


KEY WORDS magnetic resonance imaging, mitral force balance, mitral valve tethering, myocardial infarction, papillary muscles, regional wall motion, regurgitant fraction, ventricular imaging, tenting area