Relations of Augmented Systolic Annular Expansion and Leaflet/Papillary Muscle Dynamics in Late-Systolic Mitral Valve Prolapse Evaluated by Echocardiography with a Speckle Tracking Analysis

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Summary

The mechanism of systolic annular expansion in mitral valve prolapse (MVP) is not clarified. Since annular expansion is systolic outward shift of MV leaflet/chorda tissue complex at superior and outer ends, annular expansion could be related to inward (superior) shift of the complex at another inferior and inner end of the papillary muscle (PM) tip and/or systolic lengthening of the tissue complex, especially MV leaflets.

MV annulus systolic expansion, PMs' systolic superior shift, and MV leaflets' systolic lengthening were evaluated by echocardiography with a speckle tracking analysis in 25 normal subjects, 25 subjects with holo-systolic MVP and 20 subjects with late-systolic MVP.

PMs' superior shift, MV leaflets' lengthening, MV annular area at the onset of systole and subsequent MV annular expansion were significantly greater in late-systolic MVP than in holo-systolic MVP (4.6 ± 1.6 versus 1.5 ± 0.7 mm/m², 2.5 ± 1.4 versus 0.6 ± 2.0 mm/m², 6.8 ± 2.5 versus 5.7 ± 1.0 cm²/m² and 1.6 ± 0.8 versus 0.1 ± 0.5 cm²/m², P < 0.001, respectively). Multivariate analysis identified MV leaflets' lengthening and PMs' superior shift as independent factors associated with MV annular expansion.

Conclusions: These results suggest that systolic MV annular expansion in MVP is related to abnormal MV leaflets' lengthening and PMs' superior shift.

Key words: Valvular heart disease, Sudden death

Systolic augmented mitral valve (MV) annular expansion is a unique echocardiographic finding in patients with global or late-systolic MV prolapse (MVP). Although the MV annular area remains approximately constant during systole in patients with segmental or holo-systolic MVP and in normal subjects, the MV annular area considerably expands during systole in those with late-systolic MVP. Systolic annular expansion is considered to be of potential and critical importance, despite the lack of proof, with its possible influences to cause myocardial fibrosis in the left ventricular (LV) base influencing malignant ventricular arrhythmia. However, the mechanism of systolic annular expansion in patients with MVP is not yet fully clarified.

Systolic annular expansion in MVP can be expressed as "systolic outward shift of MV leaflet/chorda tissue complex at superior and outer ends" (Figure 1, red arrows). This can be related to 1) systolic inward (superior) shift of MV leaflet/chorda tissue complex at another inferior and inner end of papillary muscle (PM) tips (Figure 1, lower blue arrow) and/or 2) systolic lengthening of the tissue complex. Systolic superior shift of PMs has been confirmed. Systolic lengthening of MV leaflets has also been observed in patients with late-systolic MVP. However, significant or clear tissue elongation of chordae is not expected because of its highly limited tissue distensi-
Therefore, we hypothesized that systolic annular expansion in MVP can be related to a systolic superior shift of PM tips (Figure 1, lower blue arrow) and/or systolic lengthening of MV leaflet tissue (Figure 1, upper small black arrows). Consequently, the purpose of this study was to investigate the relation among the systolic expansion of MV annulus, superior shift of the PM tip, systolic lengthening of MV leaflet, and other cardiac structural measurements in patients with late-systolic MVP.

**Methods**

**Study population:** Consecutive 30 patients with holo-systolic MVP and 23 with late-systolic MVP who underwent conventional and three-dimensional transthoracic echocardiographic examination were retrospectively enrolled in this study, and those with only conventional echocardiography without a three-dimensional study were not included. Definition of MVP will be provided later. Age-matched 30 controls consisted of normal volunteers and those who had undergone echocardiography for clinical reasons but were finally judged to have no significant cardiac disease. Among these enrolled subjects, five controls, five controls, five patients with holo-systolic MVP, and three with late-systolic MVP were excluded because of inadequate images for the speckle tracking analysis. The remaining 25 controls, 25 patients with holo-systolic MVP, and 20 with late-systolic MVP were study subjects.

The institutional ethics committee approved this study (19-051), and the requirement to obtain informed consent was waived because of the non-invasive and retrospective nature of the study. The information of this study including anonymity, risks, and benefits were provided to the public on the homepage of the institution, and all subjects were given the opportunity to decline their enrollment in this study.

**General echocardiographic measurements:** Standard two-dimensional Doppler echocardiography was performed using an iE33 ultrasound system (Philips Healthcare, Andover, MA, USA) equipped with a 2.5 MHz transducer. In apical four- and two-chamber views, LV end-diastolic volume (LVEDV), LV end-systolic volume (LVESV), and left atrial (LA) end-systolic volume were measured by the biplane disk summation method.8) Stroke volume (SV) was measured by LV outflow tract dimensions and velocity profile. Mitral regurgitation (MR) vena contracta width (narrowest jet width by color Doppler echocardiography) was measured in the parasternal or apical view with the best MR jet visualization at the onset of systole and at end-systole.9,10) Onset of systole was defined as the echocardiographic initial frame of systolic MV closure, and end-systole was defined as end-ejection by pulsed Doppler aortic flow. Frame rates were 50-90 (mean ± SD = 67 ± 13)/second. Increase in MR vena contracta width from onset to end-systole was calculated. MR volume was quantified as the difference between LV ejection volume (LVEDV - LVESV) and forward aortic SV.

**Measurement of the dynamic MV structure:** Systolic superior shift of MV coaptation toward the LA was measured as follows. In two-dimensional echocardiographic apical views with the best visualization of the MV leaflet and its prolapse, the distance from the MV annulus level to leaflet coaptation (from the orange line to the white
Systolic superior shift of mitral valve (MV) coaptation. Depths of MV coaptation (the white broken line) in early and late systole were measured as its distance (yellow arrows) from the line connecting the MV annulus (the orange broken line) in apical echocardiographic views with the best visualization of the MV and/or mitral valve prolapse (MVP). In this normal subject (upper), MV coaptation depth slightly increases in systole (−2.4 to −1.2 mm/m²). By contrast, MV coaptation depth considerably increases in this patient with late systolic MV prolapse (MVP) (−2.3 to + 2.4 mm/m²) (lower). B: Measurements of MV leaflet length (pink arrows), papillary muscle (PM) tip to MV leaflet tip length (blue arrows) as an alternative to chordal tissue length, and MV coaptation length (green arrows). Detailed explanation is in the main text. Ao indicates aorta; LA, left atrium; and LV, left ventricle.
investigate the relationship between the systolic expansion of MV annulus and other echocardiographic measurements, including superior shift of the PM tip toward the LA, systolic lengthening of MV leaflets, the MV annular area at onset of systole, LVEDV, and EF. A multivariate analysis was further performed for variables with significant correlations as determined by the univariate analysis. Because the superior shift of PMs and the superior shift of MV coaptation showed an extremely strong correlation (these two variables are theoretically identical but measured using different methods, given the constant chordal length during systole), superior shift of MV coaptation was not included in the analysis to avoid errors from colinearity.

**Results**

**Profiles of patients:** The profiles of patients are summarized in Table I. No patient with MVP had the diagnosis of specific connective tissue disease such as Marfan syndrome and Loeys-Dietz syndrome. In the 20 patients with late-systolic MVP, 17 had Barlow type MVP, and two had thickened and large single anterior or posterior leaflet prolapse, and one had bileaflet prolapse without leaflet thickening. The LVEDV, LVESV, and EF were not significantly different between patients with late-systolic MVP and those with holo-systolic MVP. MR vena contracta width at the onset of systole was significantly reduced in patients with late-systolic MVP compared to those with holo-systolic MVP, but it was not different at end-systole between the two groups, indicating pronounced increase in the width during systole in late-systolic MVP. Superior shift of MV coaptation during systole was significantly increased in patients with late-systolic MVP compared to those with holo-systolic MVP by definition. MV annular area at the onset of systole tended to be larger and MR volume was significantly less in late-systolic MVP compared to holo-systolic MVP, reconfirming structurally large MV annulus beyond MR severity in this disease. In addition, the increase in the MV annulus area during systole (systolic MV annular expansion) was significantly greater in patients with late-systolic MVP compared to that in patients with holo-systolic MVP ($P < 0.01$), demonstrating the presence of abnormal systolic MV annular expansion in this group. Superior shift of the PM tip relative to the MV annulus was also significantly increased in late-systolic MVP ($P < 0.01$). Since the systolic inferior shift of the MV annulus relative to fixed ERP around the apex was not different between the two groups, these indicate an augmented superior shift of PM rather than an augmented inferior shift of MV annulus in patients with late-systolic MVP. AML and PML lengths, and the sum at the onset of systole tended to be longer in late-systolic MVP compared to holo-systolic MVP but without statistical significance. Both AML and PML lengths significantly lengthened at end-systole in patients with late-systolic MVP ($P < 0.01$), but these lengths only slightly increased in holo-systolic MVP. The MV coaptation length at the onset of systole was significantly longer in patients with late-systolic MVP; however, this length at end-systole was not different between the two groups. Lengths from the PM tip to the MV leaflet tip at the onset of systole were not different between the two groups and remained constant at end-systole in both groups.

**Figure 3.** Dynamic evaluation of systolic superior shift of papillary muscles (PMs) tip by any two-point speckle tracking analysis (free strain by Philips) in a normal subject and in a patient with late-systolic mitral valve prolapse (MVP). In apical four- and two-chamber views with PM visualization, distances between 1) the PM tip and fixed external reference point (ERP) around the apex (red points) and 2) the MV annulus and the ERP (blue points) were dynamically tracked and monitored. Of note is that supero-inferior direction in this echocardiographic image is reversed and consistent with the actual direction in the body (A). In a normal subject, the upper blue and lower red lines indicate the distances from the ERP to the MV annulus or PM tip, respectively. Consequently, the distance between the blue and red lines indicates the PM tip depth from the MV annulus. Since the blue and red lines are approximately parallel in systole, the PM tip depth is approximately constant during whole systole in this normal subject (black arrows) (B). A patient with late-systolic MVP, compared to panel B of a normal subject: The PM tip depth from the MV annulus is considerably reduced from the onset of systole toward end-systole (black arrows), demonstrating an abnormal systolic superior shift of the PM tip (C).
Factors associated with dynamic MV abnormalities: Table II shows factors associated with systolic expansion of the MV annulus. Using univariate analysis, systolic lengthening of MV leaflets, PM superior shift, the structurally large MV annular area at the onset of systole and younger age were associated with systolic expansion of the MV annulus. The multivariate analysis showed systolic lengthening of MV leaflets and superior PM shift as independent factors associated with systolic MV annular expansion. Of note is that the MR volume itself was not related to systolic MV annulus expansion. Figure 4 shows these relations through scatter graphs. Further multivariate analysis identified a structurally large MV annulus at the onset of systole and PM superior shift as independent factors of systolic lengthening of MV leaflets.

Discussion

This study has demonstrated that systolic lengthening of MV leaflets and systolic superior shift of PMs are closely associated with systolic expansion of the MV annulus in patients with MVP. Systolic lengthening of MV leaflets was further related to dilated MV annulus at the onset of systole. These associations are consistent with the study hypothesis. This can be interpreted as follows. Possibility #1 is that systolic lengthening of MV leaflets, superior shift of PMs and structurally large MV annulus cause abnormal expansion of MV annulus. A previous in-

### Table I. Clinical Characteristics and Basic Echocardiographic Measurements

|                     | Control ($n = 25$) | Holosystolic MVP ($n = 25$) | Late systolic MVP ($n = 20$) | $P$ (ANOVA or chi-square test) |
|---------------------|---------------------|-----------------------------|------------------------------|--------------------------------|
| Age (years)         | 58 ± 9              | 65 ± 9                      | 61 ± 10                      | 0.07                           |
| Height (cm)         | 163 ± 9             | 165 ± 11                    | 167 ± 9                      | 0.22                           |
| Weight (kg)         | 60 ± 11             | 61 ± 12                     | 58 ± 11                      | 0.61                           |
| BSA (m$^2$)         | 1.6 ± 0.2           | 1.7 ± 0.2                   | 1.7 ± 0.2                    | 0.80                           |
| Barlow type MVP     | 0 / 25              | 0 / 25                      | 17 / 20$^*$                  | < 0.001                        |
| Gender (male/female)| 17 / 8              | 14 / 11                     | 12 / 8                       | 0.42                           |
| Heart Rate (bpm)    | 65 ± 9              | 71 ± 13                     | 64 ± 12                      | 0.11                           |
| Rhythm (Sinus/AF)   | 25 / 0              | 25 / 0                      | 19 / 1                       | 0.36                           |
| Systolic BP (mmHg)  | 127 ± 17            | 139 ± 21                    | 136 ± 18                     | 0.11                           |
| Diastolic BP (mmHg) | 74 ± 13             | 78 ± 13                     | 77 ± 13                      | 0.58                           |
| LV Ejection fraction | 62 ± 10             | 103 ± 25$^*$                | 97 ± 30$^*$                  | < 0.001                        |
| LVESV (mL/m$^2$)    | 23 ± 5              | 43 ± 11$^*$                 | 42 ± 14$^*$                  | < 0.001                        |
| EF (%)              | 63 ± 6              | 58.4$^*$                    | 57 ± 5$^*$                   | < 0.001                        |
| SV (mL/m$^2$)       | 40 ± 7              | 37 ± 5                      | 39 ± 6                       | 0.32                           |
| LA volume (mL/m$^2$) | 24 ± 8              | 60 ± 28$^*$                 | 49 ± 16$^*$                  | < 0.001                        |
| VC width (OS) (mm/m$^2$) | 0.3 ± 0.5          | 3.8 ± 1.5$^*$               | 0.9 ± 0.9$^*$                | < 0.001                        |
| VC width (ES) (mm/m$^2$) | 0.2 ± 0.4          | 3.9 ± 1.3$^*$               | 3.2 ± 1.1$^*$                | < 0.001                        |
| ΔVC width (mm/m$^2$) | -0.1 ± 0.5          | 0.2 ± 0.6                   | 2.4 ± 0.9$^*$                | < 0.001                        |
| MR volume (mL/m$^2$) | 1 ± 1               | 23 ± 7$^*$                  | 16 ± 6$^*$                   | < 0.001                        |
| MV superior shift (mm/m$^2$) | 1.4 ± 0.5          | 1.4 ± 0.6                   | 4.6 ± 1.5$^*$                | < 0.001                        |
| MV annulus area (OS) (cm$^2$/m$^2$) | 4.5 ± 0.9          | 5.7 ± 1.0$^*$               | 6.8 ± 2.5$^*$                | < 0.001                        |
| MV annulus area (ES) (cm$^2$/m$^2$) | 4.3 ± 0.8          | 5.7 ± 0.9$^*$               | 8.4 ± 3.1$^*$                | < 0.001                        |
| ΔMV annulus area (cm$^2$/m$^2$) | -0.2 ± 0.3         | 0.1 ± 0.5                   | 1.6 ± 0.8$^*$                | < 0.001                        |
| Superior PM shift (mm/m$^2$) | 1.3 ± 0.4          | 1.5 ± 0.7                   | 4.6 ± 1.6$^*$                | < 0.001                        |
| MV annulus inferior shift (mm/m$^2$) | 6.1 ± 1.0          | 6.7 ± 1.1                   | 6.9 ± 1.3                    | 0.10                           |
| MV leaflet length (OS) (mm/m$^2$) | 7.1 ± 1.6          | 10.8 ± 2.5$^*$              | 12.9 ± 3.9$^*$               | < 0.001                        |
| AML + PML           | 19.9 ± 2.8          | 23.7 ± 4.6$^*$              | 27.2 ± 5.2$^*$               | < 0.001                        |
| AML                 | 12.8 ± 2.7          | 12.9 ± 4.7                  | 14.2 ± 4.8                   | 0.56                           |
| PML                 | 7.1 ± 1.6           | 10.8 ± 2.5$^*$              | 12.9 ± 3.9$^*$               | < 0.001                        |
| MV leaflet length (ES) (mm/m$^2$) | 19.6 ± 2.8          | 24.3 ± 4.4$^*$              | 29.6 ± 5.1$^*$               | < 0.001                        |
| AML + PML           | 12.4 ± 2.4          | 13.3 ± 4.5                  | 15.5 ± 4.7                   | 0.07                           |
| AML                 | 7.2 ± 1.7           | 11.1 ± 2.7$^*$              | 14.2 ± 3.7$^*$               | < 0.001                        |
| ΔAML + PML length (mm/m$^2$) | -0.3 ± 1.2         | 0.6 ± 2.0$^*$               | 2.5 ± 1.4$^*$                | < 0.001                        |
| MV coaptation (OS) (mm/m$^2$) | 2.1 ± 0.5          | 1.0 ± 1.2$^*$               | 4.0 ± 1.2$^*$                | < 0.001                        |
| MV coaptation (ES) (mm/m$^2$) | 1.6 ± 0.6          | 1.0 ± 1.1$^*$               | 1.4 ± 1.0                    | 0.05                           |
| ΔMV coaptation (mm/m$^2$) | -0.5 ± 0.4         | -0.1 ± 0.6                  | -2.6 ± 0.9$^*$               | < 0.001                        |
| PM tip to MV tip length (OS) (mm/m$^2$) | 12.6 ± 2.1         | 14.0 ± 2.6                  | 14.4 ± 2.7                   | 0.07                           |
| PM tip to MV tip length (ES) (mm/m$^2$) | 12.6 ± 2.1         | 13.9 ± 2.5                  | 14.6 ± 2.6                   | 0.05                           |
| ΔPM tip to MV tip length (mm/m$^2$) | 0.1 ± 0.5          | -0.1 ± 0.4                  | 0.2 ± 0.3                    | 0.08                           |

Values are the mean ± SD. AF indicates atrial fibrillation; AML, anterior mitral leaflet; BP, blood pressure; bpm, beat per minute; EF, ejection fraction; ES, end systole; LA, left atrium; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; MR, mitral regurgitation; MV, mitral valve; MVP, mitral valve prolapse; OS, onset of systole; PM, papillary muscle; PML, posterior mitral leaflet; SV, stroke volume; and VC, vena contracta. *$P < 0.05$ versus holosystolic MVP and †$P < 0.05$ versus control.


Table II. Factors Associated with Dynamic Changes of MV

|                              | Univariate | Multivariate |
|------------------------------|------------|-------------|
|                              | r          | P value     | Standardized β | P value |
| Systolic expansion of MV annulus |            |             |                |         |
| Age                          | -0.528     | 0.01        | -0.113         | 0.17    |
| LVEDV                        | 0.326      | 0.08        |                |         |
| EF                           | -0.209     | 0.19        |                |         |
| LA volume                    | 0.196      | 0.20        |                |         |
| MR volume                    | -0.258     | 0.09        |                |         |
| PM superior shift            | 0.840      | <0.001      | 0.456          | 0.01    |
| MV leaflet systolic lengthening | 0.852     | <0.001      | 0.506          | <0.001  |
| MV annular area (OS)         | 0.725      | <0.001      | 0.011          | 0.15    |
| MV leaflet systolic lengthening |            |             |                |         |
| Age                          | -0.496     | 0.01        | -0.166         | 0.30    |
| LVEDV                        | 0.372      | 0.05        |                |         |
| EF                           | -0.207     | 0.19        |                |         |
| LA volume                    | 0.213      | 0.18        |                |         |
| MR volume                    | -0.253     | 0.09        |                |         |
| PM superior shift            | 0.759      | <0.001      | 0.426          | 0.04    |
| MV annular area (OS)         | 0.767      | <0.001      | 0.456          | 0.02    |

EF indicates ejection fraction; LA, left atrium; LVEDV, left ventricular end-diastolic volume; MV, mitral valve; OS, onset of systole and PM, papillary muscle. All parameters related with physical size normalized by body surface area.

Figure 4. Relations between systolic expansion of mitral valve (MV) annulus and 1) systolic lengthening of MV leaflets (A) and 2) systolic superior shift of papillary muscles (PMs) (B). MV annulus expansion is related to both MV leaflet lengthening and PM superior shift.

Investigation on late-systolic MVP has demonstrated that a systolic LV-LA pressure gradient on larger MV leaflets/annulus can cause greater MV superiorly pushing force (Figure 5), shifting MV leaflets superiorly, which secondarily tract PMs to shift superiorly. Secondary PM traction has been confirmed by the disappearance of PM superior shift following surgical MV annuloplasty to reduce the MV annular area and MV superiorly pushing force. Such abnormal pathophysiology does not develop in patients with holo-systolic MVP and only modest MV annular dilatation. Results of the present study along with those of the previous studies suggest that augmented leaflet tissue distensibility, in addition to structurally large MV annulus, suggesting primary tissue fragility and leaflet tissue elongation, may further cause abnormal superior shift of PMs and contribute to systolic MV annular expansion in patients with MVP. This leaflet tissue elongation (structurally large MV annulus) and augmented distensibility may be the central and primary pathophysiology of late-systolic MVP, and prolapse itself can be a secondary consequence of this disease, which requires further studies. Possibility #2 is that primary systolic expansion of the MV annulus elongates MV leaflet tissue and tracts PMs to shift superiorly. Because MV annulus tissue lacks muscular cells to develop active motions, its motion is passive and is influenced by forces from LV pressure, LV wall, LA wall and MV leaflets. The mechanism and probability of primary MV annular expansion is not clear, but this possibility is not denied by the present study. Other interpretations may also be possible. Notwithstanding the lack of causal proof, this study in patients with MVP has demonstrated a novel finding of the close association of aug-
Figure 5. Suggested mechanism of systolic expansion of mitral valve (MV) annulus from this study. The lower panel is comparison with the upper panel: It is suggested that a structurally large MV annulus at the onset of systole causes greater MV superiorly pushing force (pink arrows) by the systolic left ventricle (LV) to the left atrium pressure gradient, shifting MV leaflets superiorly toward end-systole (small black arrows), which tracts subvalvular papillary muscles (PMs) to shift superiorly (blue arrow). The PM superior shift along with systolic lengthening of MV leaflets may in turn contribute to augmented systolic expansion of the MV annulus (red arrows) in patients with late-systolic MV prolapse (MVP). Causal relations are not yet proved, and further studies are thus required.

mented systolic expansion of MV annulus versus systolic lengthening of MV leaflets and structurally large MV annulus beyond MR severity, suggesting primarily affected leaflet tissue in this disease, and possibly a secondary superior shift of PMs.

Relation with Previous Studies: Clavel, et al. have observed systolic lengthening of MV leaflets, especially in patients with late-systolic MVP, whereas such abnormalities were not clear in those with holo-systolic MVP and normal subjects. He, et al. performed ex vivo experiments on the relation among MV annulus size, PM position, and forces acting on the MV annulus. They reported that force to dilate MV annulus increases with a larger MV annulus and slack PM position (superiorly located PM). Topilsky, et al. performed an echocardiographic analysis and found that patients with late-systolic MVP have larger MV annulus at the onset of systole and its greater expansion during subsequent systole compared to those with holo-systolic MVP. Sanfilippo, et al. found an abnormal superior shift of PMs during systole in patients with late-systolic MVP, whereas such abnormalities were not observed in normal subjects. The present study is consistent with these preceding studies and further demonstrated the close relation among systolic MV annular expansion versus systolic MV leaflets lengthening, an abnormal systolic superior shift of PMs and structurally large MV annulus at the onset of systole.

MV and LV develop mutual interactions. Primary LV dilatation causes MV leaflet tethering and secondary MR. Primary MR can cause secondary LV dilatation and dysfunction, which further causes secondary MV tethering. A large MV annulus with regional dilatation of the LV base leads to regionally reduced contraction in the LV base. A large MV annulus causes systolic superior shift of PMs and reduction in PM contraction. This study has demonstrated a novel MV-LV interaction of the close association of MV annulus systolic expansion, systolic lengthening of MV leaflets, structurally large MV annulus, and abnormal systolic superior shift of PMs.

Clinical Implications: Systolic expansion of the MV annulus is considered important as a potential factor in the pathogenesis of myocardial fibrosis in the LV base to cause malignant ventricular arrhythmia. Systolic lengthening of MV leaflets and structurally large MV annulus beyond MR severity, constituting characteristics of late-systolic MVP, seem to cause PM superior shift and contribute to the MV annular expansion. Therefore, interventions to address abnormal leaflet tissue distensibility and a structurally large MV annulus are required. For this direction, basic and molecular investigations are on their way.
In addition, potential and practical therapeutic interventions to address this fundamental pathology seems to be surgical or transcatheter MV annuloplasty. Beneficial effects of early surgery for MVP have been reported. In addition to eliminating MR, the beneficial effects may partially derive from stabilization of MV annular expansion and dynamic superior shift of PMs. Beneficial effects of surgical MV plasty for MVP on associated ventricular tachycardia have been reported. Current study may promote early surgery, especially in patients with systolic MV annular expansion and severe MR. Beneficial effects of transcatheter MV annuloplasty on MR have been reported. The present study may suggest further beneficial influences of transcatheter annuloplasty on the MV annulus and PMs’ dynamic instabilities.

When MR is eliminated by surgical MV leaflet repair, it is controversial whether ring implantation is still necessary or not. The present study may suggest the need of annuloplasty even in such cases with controlled MR to stabilize MV annulus and PMs’ dynamic abnormalities. Although MitraClip has important beneficial effects on MR, this study suggests that MitraClip without direct effects on MV annulus stabilization may not be ideal for patients with late-systolic MVP and systolic annular expansion. Limitations: Lack of proof for the causal relation among systolic superior shift of PMs, systolic lengthening of MV leaflets, structurally large MV annulus at the onset of systole and systolic MV annular expansion is the main limitation of this study. Therefore, the present study may warrant redoing Gornick’s experiment. Gornick, et al. mechanically tracted PMs superiorly during systole and introduced ventricular arrhythmia in intact canine hearts. This is still an innovative and important animal model of ventricular arrhythmia in MVP. If MV annulus systolic expansion is introduced by mechanical PM traction toward MV or LA, it will at least partially prove that superior PM shift in systole contributes to MV annulus systolic expansion.

Abnormal myocardial fibrosis develops, especially in LV base and PMs, in patients with MVP. The present study suggests the possibility of augmented leaflet tissue distensibility, and a structurally dilated MV annulus may promote systolic dynamic MV annular expansion with a PM superior shift. However, relation between these PMs and MV annulus dynamic instabilities and myocardial fibrosis was not investigated. In general patients with MVP, those with bileaflet prolapse and of a younger age and female gender are at high risk of sudden death. Identification of additional echocardiographic characteristics with higher risk will benefit patients. Clinical studies to compare dynamic MV annulus systolic expansion and PMs’ superior shift versus LV/PM myocardial fibrosis and ventricular arrhythmia are required. The number of studied subjects is small, and studies with larger sample sizes are required. Consecutive patients with MVP and conventional and three-dimensional echocardiographic examination were enrolled; however, those with only conventional echocardiography were not included with a potential selection bias. Although all systolic annular expansion, leaflet lengthening and PMs’ superior shift are three-dimensional phenomena, measurements in this study were two-dimensional.

Conclusions

Systolic MV annular expansion in MVP is related to systolic abnormal lengthening of MV leaflets, a systolic superior shift of PMs and a structurally large MV annulus. These may promote further studies to investigate 1) causal relations among MV annulus expansion, PM traction, leaflet distensibility, and a structurally large MV annulus; 2) relations between MV annulus and PMs dynamic instabilities versus myocardial fibrosis and ventricular arrhythmia; and 3) beneficial influences of surgical or transcatheter MV annuloplasty to stabilize dynamic MV annulus and PMs’ abnormalities in patients with MVP.

Disclosure

Conflicts of interest: The authors report no relationships that could be construed as a conflict of interest.

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