Assessment of Changes in Mitral Valve Configuration With Multidetector Computed Tomography
Impact of Papillary Muscle Imbrication and Ring Annuloplasty

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**Background**—The optimal surgical procedures in functional mitral regurgitation remain controversial. We applied papillary muscle imbrication (PMI) combined with undersized mitral annuloplasty (UMAP). Multidetector computed tomography (MDCT) provides images of different phases of the cardiac cycle, allowing an assessment of the geometry. In the present study, we evaluated the mitral valve configuration and subvalvular apparatus before and after UMAP and/or PMI using MDCT imaging.

**Methods and Results**—We studied 26 patients with functional mitral regurgitation (3+ to 4+) with an ejection fraction ≥35% who underwent diagnostic MDCT examinations before and early after the operation. Of these, 15 underwent UMAP and PMI (UMAP+PMI group) and 11 underwent UMAP alone (UMAP group). The annular anteroposterior diameter, tenting height, tenting area, and interpapillary muscle distance at end-systole were quantified. The annular anteroposterior diameter, tenting height, and tenting area were significantly decreased after the operation in both groups. Whereas the average change in annular anteroposterior diameter, tenting area, and interpapillary muscle distance did not differ between the 2 groups, the average change in tenting height was greater in the UMAP+PMI group than in the UMAP group (5.1 ± 1.3 versus 3.8 ± 2.3 mm, P = 0.036). There was a significant correlation between the change in interpapillary muscle distance and the change in tenting height in the UMAP+PMI group (r = 0.788, P = 0.0005).

**Conclusions**—Our results examined with MDCT indicated that UMAP combined with PMI improved leaflet tethering compared with UMAP, reflecting differences in the effects of the surgical procedures used, and suggested that concomitant PMI might be beneficial in some cases. (*Circulation*. 2010;122[suppl 1]:S29–S36.)

**Key Words:** mitral valve ▪ cardiomyopathy ▪ structure ▪ valves ▪ computed tomography

Functional mitral regurgitation (MR) results from left ventricular (LV) remodeling that occurs secondary to intrinsic myocardial disease or infarction. The remodeling causes mitral valve leaflet tethering by the outward and apical displacement of the papillary muscles and annular dilatation, resulting in malcoaptation of the leaflets.1–4 Since Bolling et al1,2 first reported the feasibility of surgical treatment for severe MR in patients with end-stage cardiomyopathy, undersized mitral annuloplasty (UMAP), a restrictive mitral annuloplasty procedure, has become the preferred surgical approach for treating severe ischemic or functional MR complicated with advanced cardiomyopathy. However, Calafiore et al5 found that ring annuloplasty is not effective in cases in which the tethering is strong, and McGee et al6 reported that the short- and midterm outcomes of ring annuloplasty are not satisfactory. Furthermore, residual/recurrent MR after UMAP is observed in up to 30% of patients after UMAP alone.6

Recurrent MR adversely affects the New York Heart Association (NYHA) functional class and decreases survival.7,8 The high incidence of functional MR (FMR) appears to be a consequence of performing the repair only at the annular level, and UMAP alone cannot address the leaflet tethering. Therefore, it is essential to develop additional techniques to treat FMR. Previous studies revealed that papillary muscle displacement plays an important role in FMR. Therefore, we have recently begun to apply papillary muscle imbrication (PMI) with UMAP to correct the displaced papillary mus-
cles, although PMI still does not address the ventricular cause of FMR.

Several investigators have assessed the geometry of the mitral valve and the effects of UMAP by techniques commonly used in daily clinical practice, such as 3-D or 2-D echocardiography. However, the effects of PMI on mitral valve geometry have not been completely elucidated. Multidetector computed tomography (MDCT) is an emerging technique that is considered useful for assessing mitral valve geometry. Compared with 4- and 16-row MDCT, 64-row MDCT provides faster temporal resolution and more accurate contour definition. Moreover, with ECG-gated image acquisition, cardiac MDCT shows different planes of the whole heart and enables the assessment of mitral valve geometry at different phases.

In the present study, we evaluated the configuration of the mitral valve and subvalvular apparatus before and after UMAP with or without PMI, using 64-row MDCT.

Methods

Patients and Study Protocol

The records of 20 patients with FMR caused by end-stage cardiomyopathy refractory to medical therapy, who underwent UMAP with adjunctive PMI at Osaka University Hospital between March 2007 and August 2009, were reviewed (UMAP+PMI group). For comparative purposes, records from 11 patients with FMR due to end-stage cardiomyopathy, who underwent UMAP alone at Osaka University Hospital between May 2006 and February 2007 (UMAP group) were also reviewed. The inclusion criterion was the presence of functional mitral regurgitation diagnosed on the basis of (1) LV dysfunction with an ejection fraction (EF) ≤35% and (2) an MR grade equal to or greater than 3+. Patients with mitral valve thickening, prolapse, annular calcification, vegetation, fenestration, or rheumatic mitral valve changes were excluded. The present study analyzed the records of the 26 patients who underwent a 64-row MDCT examination before and after the operation. The other 5 patients did not undergo MDCT because of an unstable hemodynamic condition.

After their admission, the patients underwent transthoracic echocardiography to assess their cardiac function and evaluate their mitral valve function and morphology. All 26 patients had symptoms of heart failure, and were rated as NYHA functional class III or IV. All of them were receiving optimized medical regimens, including β-blockers, angiotensin-converting enzyme inhibitors or angiotensin-receptor blockers, and diuretics. The patients’ baseline characteristics are presented in Table 1.

Informed consent was obtained from all patients, and the study was approved by our institutional ethical committee.

Surgical Procedure

The procedure was performed under normothermic cardiopulmonary bypass conditions with intermittent antegrade and retrograde cardioplegia through a median sternotomy and right-sided left atriotomy. All patients underwent UMAP without any other mitral reconstructive techniques (Table 2). We have used PMI in addition to UMAP to correct the displaced papillary muscles since March 2007. The papillary muscles were identified through the mitral valve orifice in each patient and carefully inspected (Figure 1A). In our method, 3-0 Prolene mattress sutures (Ethicon, Inc, Somerville, NJ) with felt strips were passed through the basal to middle portion of the anterolateral and posteromedial papillary muscle. In each case, the suture was snared, and the basal to middle portion of both papillary muscles was imbricated, thus directly reducing the distance between them (Figure 1B). As we gained experience with this procedure, we began placing wider mattress sutures, sometimes 2 pairs of them, to overlap the papillary muscles as close as possible to their tips. All the

<table>
<thead>
<tr>
<th>Variables</th>
<th>UMAP+PMI (n=15)</th>
<th>UMAP (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>65±11</td>
<td>64±8</td>
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<tr>
<td>Male, n (%)</td>
<td>12 (80)</td>
<td>8 (73)</td>
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<tr>
<td>Body surface area, m²</td>
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<td>1.64±0.14</td>
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<td>NYHA</td>
<td>3.0±0.5</td>
<td>2.9±0.5</td>
</tr>
<tr>
<td>LVEF</td>
<td>0% to 15%, n (%)</td>
<td>2 (13) 1 (9)</td>
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<tr>
<td></td>
<td>16% to 25%, n (%)</td>
<td>5 (33) 5 (45)</td>
</tr>
<tr>
<td></td>
<td>26% to 35%, n (%)</td>
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<tr>
<td>Etiology</td>
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<td>Nonischemic, n (%)</td>
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<tr>
<td>Coronary disease</td>
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<tr>
<td></td>
<td>2 Vessels, n (%)</td>
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<td>3 Vessels, n (%)</td>
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<td></td>
<td>Peripheral arterial disease, n (%)</td>
<td>1 (7) 1 (9)</td>
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<tr>
<td></td>
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<td></td>
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<td>3 (20) 2 (18)</td>
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<td>Atrial fibrillation/flutter, n (%)</td>
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<td></td>
<td>History of ventricular tachycardia, n (%)</td>
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<tr>
<td></td>
<td>Previous PCI, n (%)</td>
<td>5 (33) 3 (27)</td>
</tr>
<tr>
<td></td>
<td>Previous ICD, n (%)</td>
<td>1 (7) 0 (0)</td>
</tr>
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</table>

LVEF indicates LV ejection fraction; LMT, left main trunk; COPD, chronic obstructive pulmonary disease; PCI, percutaneous coronary intervention; and ICD, implantable cardioverter-defibrillator. Categorical data are presented as numbers of patients and percentage of sample; continuous data are presented as mean value±SD.

patients then underwent UMAP (downsizing of the annulus by 2 ring sizes) with the implantation of an undersized semirigid ring (Carpentier-Edwards Physiolog; Edwards LifeSciences, Irvine, Calif). The implanted ring sizes are listed in Table 2.

Concomitant coronary artery bypass grafting was performed for ischemic cardiomyopathy, nearly always with the left internal thoracic artery on the left anterior descending artery. Tricuspid annuloplasty was performed with a Carpentier Edwards MC² ring (Edwards Lifesciences) for an annulus diameter that exceeded 40 mm.

MDCT Angiography

MDCT angiography was performed using a commercially available 64-slice multidetector row scanner within 1 month before surgery and 2.2 months after surgery.

Each patient was positioned in the scanner so as to yield whole-heart MDCT images in the cranio-caudal direction during a single breath-hold. During the scan, the ECG signal was digitally recorded. After an initial scout image and a timing bolus scan, a volume data set (collimation, 64×0.625 mm; gantry rotation time, 350 ms; mean scanning time, approximately 5 seconds) was acquired covering the distance from the carina to the diaphragm with retrospective electrocardiographic gating for image reconstruction.
To enhance the LV cavity, 0.8 mL/kg of nonionic contrast medium was administered at a flow rate of 4 mL/s. Ten data sets were obtained at 10% R-R interval increments throughout the cardiac cycle (5% to 95%).

Three-dimensional reconstruction and image analyses were performed on a workstation for quantitative analysis. First, a cross-sectional plane of the mitral valve that clearly showed both mitral commissures was obtained from multiple long axes to reveal the end-systolic multiplanar reformation. The end-systolic phase was defined as the cardiac phase with the smallest LV cavity volume, and the anteroposterior plane perpendicular to this plane was determined. In that plane, which passed through the middle of the anterior and posterior mitral annulus, special attention was paid to capture the mitral leaflet coaptation at end-systole (Figure 2). In addition, the reconstruction of short-axis images was done with special attention to visualizing the tips of the papillary muscles at both end-systole and end-diastole (Figure 3).

Mitral Valve Configuration

The measured variables were (1) the annular anteroposterior diameter, (2) tenting height, (3) tenting area, and (4) interpapillary muscle distance (Figures 2 and 3). The annular anteroposterior diameter was measured as the diameter at the center of the anterior and posterior mitral annulus in the long-axis view at end-systole. The tenting height was measured as the perpendicular distance between the coaptation point of the mitral leaflets and the line connecting the annular hinge points in the long axis view at end-systole. The tenting area was obtained by tracing the triangle enclosed by both leaflets and a septolateral oriented line in the long-axis view at end-systole. The interpapillary muscle distance was measured as the distance between the anterior and posterior papillary muscle tips in the short-axis view at end-systole and end-diastole. For an index of the shape of the left ventricle, LV end-diastolic and end-systolic sphericity indices were calculated as the ratio of the minor axis to the major axis length of the LV.

Echocardiography

Standard 2-D and Doppler echocardiographic examinations with color-flow mapping were performed serially on all patients 1 week before and 2.0 months after the operation (commercially available GE Medical Systems, Vivid 7, Milwaukee, Wis). Color-flow imaging was used to determine the presence or absence of MR, and the degree of MR was graded as follows: none-to-trivial (0 to 1+), mild (2+), moderate (3+), or severe (4+), based on the color Doppler echocardiography results at end-systole. Echocardiographic mea-

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**Table 2. Surgical Data**

<table>
<thead>
<tr>
<th>Variables</th>
<th>UMAP + PMI (n=15)</th>
<th>UMAP (n=11)</th>
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<tr>
<td>UMAP, n (%)</td>
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<td>11 (100)</td>
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<td>Ring size used</td>
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<td>Physio Annuloplasty Ring No. 24, n (%)</td>
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<td>3 (27)</td>
</tr>
<tr>
<td>Physio Annuloplasty Ring No. 26, n (%)</td>
<td>11 (73)</td>
<td>7 (63)</td>
</tr>
<tr>
<td>Physio Annuloplasty Ring No. 28, n (%)</td>
<td>2 (13)</td>
<td>1 (9)</td>
</tr>
<tr>
<td>Papillary muscle imbrication, n (%)</td>
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<td>0 (0)</td>
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<tr>
<td>Concomitant procedures</td>
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<td></td>
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<tr>
<td>CABG, n (%)</td>
<td>10 (67)</td>
<td>8 (73)</td>
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<tr>
<td>Average No. of distal anastomoses, n</td>
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<td>TAP, n (%)</td>
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<tr>
<td>Maze, n (%)</td>
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<td>3 (27)</td>
</tr>
<tr>
<td>CRT-D implantation, n (%)</td>
<td>5 (33)</td>
<td>3 (27)</td>
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<tr>
<td>Intraoperative data</td>
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<tr>
<td>CPB time, min</td>
<td>203±38</td>
<td>199±52</td>
</tr>
<tr>
<td>AXC time, min</td>
<td>104±29</td>
<td>102±31</td>
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</table>

CABG indicates coronary artery bypass graft; TAP, tricuspid annuloplasty; CRT-D, cardiac resynchronization therapy defibrillator; CPB, cardiopulmonary bypass; and AXC, aortic cross-clamp. Categorical data are presented as numbers of patients and percentage of sample; continuous data are presented as mean value ±SD.

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**Figure 1.** A. The papillary muscles were identified and carefully inspected. B. 3-0 Prolene mattress sutures (Ethicon, Inc, Somerville, NJ) with felt strips were passed through the basal to middle portion of the anterolateral and posteromedial papillary muscle.

**Figure 2.** Cardiac MDCT image and evaluation of mitral valve geometric parameters (1–3): annular anteroseptal diameter (2–4); tenting height. The triangle (1 to 2–3) shows the tenting area.

**Figure 3.** Reconstruction of short-axis images was done with special attention to visualizing the tips of the papillary muscles at both end-systole and end-diastole. The interpapillary muscle distance was measured as the distance between the anterior and posterior papillary muscle tips in the short-axis view.
surgical procedures included the LV end-diastolic dimension (LVEDD) and end-systolic diameter (LVESD), left atrial diameter, LV ejection fraction (LVEF), and other routine variables. All echocardiographic data were analyzed in random order by trained readers who were blinded to the clinical data and timing of the echocardiogram.

Statistical Analysis
Continuous variables were expressed as mean ± 1 SD. Normally distributed variables were compared before and after surgery using Student t test for paired or unpaired data, and nonnormally distributed variables were compared by the Wilcoxon signed rank test or the Mann-Whitney U test. Correlations between variables were tested with Pearson’s correlation analysis. A probability value less than 0.05 was considered to be statistically significant. All statistical calculations were performed using SPSS for Windows (SPSS Inc).

Results
Operative Data
Intraoperative data are presented in Table 2. There were no significant differences for cardiopulmonary bypass time or aortic cross-clamp time between the 2 groups (P > 0.05). There were no differences of group differences for the type or size of the annuloplasty device used or for the number of concomitant procedures (P > 0.05 for all).

Clinical Outcomes
There were no cases of intraoperative death or mortality. The mean follow-up period was 13.7 ± 11.7 months (range, 1 to 41 months). After the operation, all 26 patients showed trivial or less than trivial MR, and the severity score had decreased significantly, from 3.3 ± 0.5 to 0.5 ± 0.5 (P < 0.01). During the follow-up period after discharge, 2 of the 15 patients (13%) in the UMAP+PMI group and 1 of the 11 patients (9%) in the UMAP group required hospitalization for heart failure and 1 of the 11 patients (9%) in the UMAP group required a second mitral surgery for infectious endocarditis. Overall, the NYHA functional class improved from III or IV to I or II (P < 0.05).

The patients’ serum brain natriuretic peptide level decreased from 903 ± 792 pg/mL preoperatively to 504 ± 618 pg/mL at discharge (P = 0.0004).

Hemodynamics and LV Measurements
The LVEF tended to increase, but the change did not reach statistical significance postoperatively. The average increase in LVEF (calculated as the postoperative value minus the preoperative value) did not differ between the 2 groups. The LVEDD and LVESD changed significantly after surgery in both groups (Table 3). The average decrease in volume did not differ between the 2 groups.

Mitral Valve Configuration
The preoperative and postoperative parameters are shown in Table 4. The annular anteroposterior diameter, tenting height, and tenting area were significantly decreased in both groups (Figure 4 and Table 4). The interpapillary muscle distance was significantly decreased at end-systole and end-diastole.
from the preoperative values in the UMAP+PMI group. Although these parameters tended to decrease in the UMAP group, the changes did not reach statistical significance. The sphericity index did not change significantly at end-systole or end-diastole in either group.

In the between-group comparisons, the average change in the annular anteroposterior diameter, tenting area, end-diastolic and end-systolic interpapillary muscle distance, and end-diastolic and end-systolic sphericity index (calculated as the postoperative value minus the preoperative value) did not show a significant difference. However, the average change in tenting height was greater in the UMAP+PMI group than in the UMAP group. This trend probably reflects differences in the effects of the surgical procedures used, and suggests UMAP with concomitant PMI may be beneficial in some cases.

Pearson correlation analysis revealed a highly significant inverse correlation between the change in tenting height and change in interpapillary muscle distance at end-systole and end-diastole in the UMAP+PMI group (Figure 5). There was no significant correlation between the change in tenting height and the change in interpapillary muscle distance at end-systole and end-diastole in the UMAP group (r=0.077 and r=0.115, respectively).

Discussion
The major finding of this study was that mitral leaflet tethering was remarkably improved after valvular and/or subvalvular mitral repair examined with 64-row MDCT. We found that UMAP plus PMI was more effective in reducing tenting height in patients with FMR compared with UMAP alone. We also found a significant correlation between the postoperative decrease in tenting height and the postoperative improvement in interpapillary muscle distance.

In the present study, we compared the efficacy of UMAP+PMI with that of UMAP in patients with FMR.
Quantitative descriptions of the mitral valve configuration using 64-row MDCT demonstrated that our combined UMAP and PMI procedure improved the mitral leaflet tethering as compared with UMAP alone. To the best of our knowledge, the use of MDCT to evaluate the effects of UMAP combined with PMI and UMAP alone on mitral valve geometry is novel. The use of PMI as an adjunctive subvalvular repair, which we have successfully adopted in combination with UMAP, is a surgical option that may prove beneficial.

Hvass et al\textsuperscript{44} reported the use of a papillary muscle sling, and Menicanti et al\textsuperscript{15} used PMI. Their methods share the same concept as ours, which is that reducing the increased inter-papillary muscle distance diminishes the degree of tethering, although they used different surgical approaches (ie, from the LV instead of the left atrium [LA]). However, no report provides conclusive evidence for the impact of PMI on mitral leaflet tethering. Our results show that UMAP with PMI improved the interpapillary muscle distance, which was correlated with an improvement in tenting height. Although the increased improvement in mitral leaflet tenting and reduced muscle distance in the more-dilated LVs may simply be owing to their increased dilation at the time of surgery, the present results suggest that the improvement in leaflet tethering was due in part to adding the PMI surgical technique for subvalvular repair via the LA.

Because functional MR can result from a number of different mechanisms, UMAP, although the current surgical treatment of choice, does not always provide durable repair. Previous investigators have reported recurrence in 15\% to 30\% of patients; the wide range is caused by the different population profiles and follow-up times. In our small series, 2 patients (13.3\%) treated with UMAP+PMI and 1 patient (9\%) treated with UMAP alone had heart failure during the mean follow-up period of 13.7±11.7 months after discharge, which is better than the heart-failure rate in other reports.

The high rate of MR recurrence associated with UMAP has led a number of investigators to seek reliable predictors for the recurrence of FMR despite UMAP. Braun et al\textsuperscript{16} indicated that a preoperative LVEDD of 65 mm or more predicts a stronger likelihood of MR recurrence after annuloplasty remodeling. Calafiore et al\textsuperscript{1} introduced the index of mitral valve coaptation depth for predicting the recurrence of MR after annuloplasty. In this report, the postoperative NYHA functional class was similar to the preoperative value in patients whose mitral valve coaptation depth was 11 mm or more, even though the residual FMR decreased. Roshanali et al\textsuperscript{19} found that a preoperative interpapillary distance ≥20 mm was a reliable predictor of late MR after annuloplasty. Onorati et al\textsuperscript{17} reported that a coaptation depth ≥5 mm at discharge may be an early indicator of a higher risk for recurrence. All of these data support the need for interventions to address ventricular tethering or papillary muscle tethering to reduce the risk of MR recurrence.

The present study focused on the geometric changes associated with UMAP with or without PMI. Our results indicated that combining UMAP with PMI might be beneficial for improving mitral leaflet tethering compared with UMAP alone, even in patients with extensive tethering, by reducing the annular anteroposterior diameter and interpapillary muscle distances. These results are in line with those of several previous reports.\textsuperscript{18–20} Nevertheless, complex phenomena, including papillary muscle displacement, annular dilation, and loss of saddle shape among others, contribute to FMR. Furthermore, ventricular pathology is likely to be an important cause of FMR. Although surgical techniques, including UMAP and PMI, are improving, these procedures still do not address the role of the ventricle in FMR.

**LV Volume and Function**

In this small series, we achieved an improvement in LV function and a decrease in LV dimension. There have been a number of studies on global LV functioning after the correction of FMR in patients with severe LV dysfunction. Some investigators have reported a substantial improvement in systolic performance,\textsuperscript{2,3,6,9,17,21,22} whereas others failed to find a significant improvement. Our results are consistent with those of recent studies using echocardiography. The total end-diastolic and end-systolic diameters decreased significantly and the LVEF tended to increase after UMAP with or without PMI.

Previous studies have used 2-D and 3-D echocardiography to investigate the pathophysiology of FMR.\textsuperscript{4,17–19,23} Although 2-D echocardiography is the most common method for evaluating the LV dimension and systolic function in clinical practice, it cannot assess the 3-D geometry of the mitral apparatus. On the other hand, the accuracy of 3D echocardiography can be compromised by the need for geometric models, because image acquisition is dependent on the acoustic window.

Recent advances in steady-state free precession sequencing for cardiac MDCT have resulted in a shorter acquisition time and improved image quality. Considering the relatively short
acquisition time and adequate quality of the reconstructed images, 64-row MDCT is a useful clinical tool for assessing the configuration of the mitral valve in patients with FMR. Cardiac MRI is presently considered the gold standard for LV geometry evaluation, as it provides excellent temporal and spatial resolution, along with a high degree of accuracy and reproducibility of quantitative measurements, although it is limited by a long scanning period and cannot be used for patients with a pacemaker. Therefore, 64-row MDCT has been recently proposed as an alternative to 2-D and 3-D echocardiography.

Clinical Implications

On the basis of the present results, we favor PMI in addition to mitral annuloplasty with an undersized complete ring to improve mitral leaflet tethering by directly decreasing the interpapillary muscle distance, thereby decreasing the tenting height. In the present study, even when the mitral valve was extensively tethered, our approach was successful, with satisfactory early results. In our patients, this additional procedure, which directly addressed the subvalvular apparatus, prevented or at least delayed the recurrence of MR. In addition, the PMI technique is simple to perform and reproducible.

Limitations

Considerable caution must be exercised in extrapolating from the present results. The major limitations of our study are that it was not conducted in a randomized manner and involved a rather small number of patients. On the other hand, the single-center design of the study guaranteed uniformity of the surgical technique and perioperative care. The 100% follow-up is another strength. At present, the long-term results of our technique are unpredictable, although it will be necessary to obtain long-term outcome data to establish its suitability. Furthermore, additional investigation that includes mid-term and/or long-term follow up is needed to assess whether PMI, as an adjunctive subvalvular repair, changes the rate of MR recurrence, heart failure, and/or survival.

Another limitation of this study is the need for concomitant surgical procedures to address the complex, heterogeneous etiologies of functional MR. Our results were obtained from patients who underwent UMAP with or without PMI, but the study did not include a control group of patients who did not have either procedure. To differentiate between the effects of UMAP and PMI, future investigations that include other study groups to compare with patients undergoing PMI to UMAP and PMI, future investigations that include other etiologies of functional MR. Our results were obtained from a series of 2-D images was feasible and clinically useful.

Conclusion

Our simplified measurement method provided quantitative and morphological descriptions of the mitral leaflet configuration, using 64-row MDCT, and provided important information regarding the effects of PMI as a subvalvular repair procedure for regulating FMR.

Disclosures

None.

References

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