Quantitative Assessment of Mitral Apparatus Geometry Using Dual-Source Computed Tomography in Mitral Regurgitation
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Summary
To quantitatively assess the geometric changes in mitral valve apparatus in mitral regurgitation (MR) by dual-source computed tomography (DSCT) and to analyze its impact on MR. The study subjects consisted of 20 controls, 20 patients with mild MR, and 30 patients with moderate to severe MR, all of whom underwent DSCT. The geometric parameters of the mitral valve were measured by CT and compared among the 3 groups. The correlations between DSCT measurements and MR severity were also analyzed.

As regurgitation worsened, our results showed progressive enlargements of the mitral annular area, anteroposterior diameter, and mitral valve tenting area at the central level. Moreover, a higher mitral valve sphericity index and longer distance between the heads of the papillary muscles reflected a more outward displacement of the papillary muscles. The mitral annular area and tenting area at the central level had strong correlations with regurgitation severity.

DSCT is available to quantitatively assess mitral valve morphology and provide additional information regarding its geometry. The mitral annular area and tenting area at the central level were the strongest determinants of MR severity.

Key words: Mitral valve morphology, Mitral leaflets, Mitral annulus, Papillary muscles

Mitral regurgitation (MR) is a common cardiac disease caused by a functional or structural abnormality of the mitral valve. The prevalence of MR tends to increase with age and has a very high rate in elderly people.1,2 Regardless of whether the regurgitation is caused by a primary anatomical abnormality of the mitral valve3,4 or secondary to left ventricular dysfunction,5 moderate to severe MR is associated with a lower survival rate. The progression of significant MR may result in pulmonary hypertension and heart failure.

The mitral valve apparatus is a complex 3-dimensional structure consisting of the mitral annulus (MA), leaflet, chordae tendinae, papillary muscles (PMs), and the attached left ventricular wall. Every component works in a coordinated, precise manner to prevent blood flowing back into the left atrium during cardiac systole. A comprehensive, accurate assessment of the mitral apparatus is very important for determining the optimal treatment plan, deciding the timing of surgical intervention, and determining the prognosis. In recent years, there have been several studies on mitral valve structure.5-8 However, most studies focused on one part of the mitral apparatus. Due to the complexity and delicacy of the mitral valve, assessing the apparatus quantitatively and comprehensively remains a considerable challenge for physicians.

Coronary computed tomography (CT) angiography is currently used as an invasive tool to evaluate the coronary anatomy and exclude significant ischemic heart disease in patients referred for valvular surgery with high sensitivity and specificity.9-12 Recent advances in multi-detector CT (MDCT)/dual-source CT (DSCT) have provided a better understanding and assessment of the heart valves,13,14 with high spatial resolution, excellent image quality, and comprehensive cardiac data. Therefore, this study aimed to quantitatively assess the anatomy and geometry of the mitral valve apparatus using ECG-gated 64-slice DSCT.

Methods
Study population: This retrospective single-center study was performed at Shanghai Xinhua Hospital, and was approved by the Institutional Review Board. Informed written consent from each patient was obtained prior to the study. A total of 80 con-
secutive patients, who underwent cardiac DSCT scanning, were studied. These patients all had mild to severe MR and were in accordance with the guideline-based indications for coronary angiography to exclude coronary artery disease (CAD). The exclusion criteria included previous myocardial infarction or significant coronary artery disease by CT coronary angiography (ischemic MR, \( n = 2 \)), prior intracardiac operation (\( n = 5 \)), mitral stenosis (\( n = 8 \)), significant aortic regurgitation (\( n = 10 \)), and poor quality CT images (\( n = 5 \)). The general exclusion criteria for contrast-enhanced CT included renal dysfunction (serum creatinine level > 150 mmol/L) and hypersensitivity to iodine. The control group included patients with normal echocardiographic and cardiac computed tomographic results.

Cases were divided into 3 groups according to the degree of MR: group 1 included patients without MR, group 2 comprised patients with mild MR, and group 3 comprised patients with moderate to severe MR.

**Echocardiography:** Two-dimensional TTE examinations were performed in all subjects using a Philips IE33 echocardiography (Philips Medical Systems, Andover, MA, USA) by an echocardiographic expert with more than 5 years working experience. MR severity was characterized using the American College of Cardiology/American Heart Association (ACC/AHA) guidelines.\(^{19,20}\) Left ventricular (LV) ejection fraction (EF) was determined by Simpson’s biplane method.\(^{21}\)

**CT coronary angiography:** All patients were examined with a 64-slice DSCT scanner (SOMATOM Definition, Siemens Medical Solutions, Erlange, Germany) using the prospective ECG-triggering spiral mode, with the following parameters: 120 Kv, 560 mAs, collimation = 32 × 0.6 mm, pitch = 0.2-0.5 (depending on the heart rate), and rotation time = 330 ms. No one was taking beta-blockers before the scan (mean heart rate 76 ± 10 bpm, range from 48 to 97 bpm). Scanning was conducted using bolus tracking and delay triggering technology, and the region of interest (ROI) was set at the ascending aorta. When the CT value of ROI exceeded 100 Hu, the scanning was initiated. Contrast medium (Iohexol 320 mg I/mL, GE Healthcare, Shanghai, China) was injected into each patient by a dual-head power injector (Tyco OptiVantage DH, USA) at an injection rate of 5 mL per sec, and a 50 mL saline flush was administered at the same flow rate.

**CT data reconstruction and analysis:** The original data was reconstructed in Syngo Circulation software. Reconstruction thickness was 0.7 mm, and 10 image series of the cardiac cycle (0% of the R-R interval as early systole, 90% of the R-R interval as late diastole, reconstructed in 10% increments from 0% to 90%) was detained. The FOV (field of view) was 180 × 180 mm, 512 × 512 pixel.

Using Inspace, we adjusted the original coronal, sagittal, and transverse planes to the following 3 aspects (Figure 1: 1) closure line sections; perpendicular to the mitral annulus plane, through the mitral valve closure line and apex; 2) valve sagittal section; a perpendicular plane to the mitral closure line and visualizing the valve leaflets and clearly displaying both sides of the closing point; and 3) mitral annulus section; a short-axis plane perpendicular to the two above-mentioned planes, at the level of the mitral annulus. Through all 10 phases (as a whole cardiac cycle), we selected the phases with the minimum and maximum left ventricular volume.

The parameters measured included the following:

1) Mitral annulus parameters: The anteroposterior diameter (AP) and intercommissural diameter (CC) was measured from the mitral annulus section view in systole (A). The mitral annular area was quantified from the mitral annulus section view in systole (B). AO indicates aorta; and MAA, mitral annular area.

2) Mitral leaflet parameters: A plane parallel to mitral annulus sections, clearly showing both mitral commissures, was reconstructed. Three anteroposterior planes perpendicular to this plane were defined to assess the geometry of the anterolateral, central, and posteromedial parts of the mitral leaflets (Figure 3A). In the above 3 planes, the tenting height, tenting area, and anterior and posterior leaflet angles were measured in systole (Figure 3B). The leaflet angle was defined as the angle at which each leaflet met the mitral annulus plane, which can infer the degree of leaflet tethering.

3) Mitral valve sphericity: This parameter was defined as the ratio of the distance between the base of the papillary mus-
cles (X) and the vertical distance between this plane and the mitral annulus plane (Y). We measured the distance between the heads of the PMs at the same time (Figure 4).

4) Left ventricular morphology parameters: These parameters included the left ventricular short axis length (the distance between the base of two papillary muscles), long axis length, and left ventricular sphericity (left ventricular long axis/short axis).

All values were the mean value of 3 measurements by the same observer.

Statistical analysis: Statistical analyses were performed using SPSS (Statistical Package for the Social Sciences, version 19.0, Chicago, IL, USA). Continuous variables are presented as the mean ± SD and categorical variables as frequencies or percentages. Baseline characteristics were compared using the analysis of variance (ANOVA) or χ² test. Parameters of mitral apparatus among the 3 groups were analyzed using ANOVA test, and the Least Significant Difference (LSD) test was used as a post-hoc test among the groups. Correlation of DSCT parameters of mitral apparatus and MR severity was tested by Pearson’s correlation, and univariate and multivariate regression analysis. All parameters measured in the CT data set were corrected for body surface area. A P value of < 0.05 was considered as significant.

Results

Baseline characteristics: A total of 70 subjects (mean age, 63.8 ± 10.2 years; 33 women) were divided into a control group (n = 20), mild MR group (n = 20), and moderate to severe MR group (n = 30). There were no significant differences in age, sex, body surface area, or systolic and diastolic blood pressures among the 3 groups. The baseline characteristics of the 3 groups are shown in Table I.

Geometry measurements of the mitral valve: All measurements of the mitral annulus and leaflets in the 3 groups are shown in Table II. The group with more severe MR showed a significant, progressive enlargement of the mitral annular area. Compared to the other subjects, patients with moderate to severe MR had significantly larger mitral annular circumference and anteroposterior and commissural diameters, whereas no differences were found between the control and mild MR groups.

In particular, the mitral valve tenting area at the central level was significantly larger in the moderate to severe MR group, while the P value (P = 0.063) was just close to a statistically significant difference between the mild MR group and the controls. Compared to the other two groups, the moderate to severe MR group had a significantly larger posterior leaflet angle at the central level. However, regardless of the anterolateral or posteromedial level or angle of the anterior leaflet, no differences were observed. There was no difference in the tent-

Table I. Baseline Characteristics of the Study Population

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1 (n = 20)</th>
<th>Group 2 (n = 20)</th>
<th>Group 3 (n = 30)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>63.30 ± 9.25</td>
<td>67.30 ± 8.76</td>
<td>61.90 ± 11.33</td>
<td>0.179</td>
</tr>
<tr>
<td>Gender, M/F</td>
<td>8/12</td>
<td>12/8</td>
<td>17/13</td>
<td>0.429</td>
</tr>
<tr>
<td>Body surface area, m²</td>
<td>1.71 ± 0.12</td>
<td>1.75 ± 0.12</td>
<td>1.68 ± 0.20</td>
<td>0.271</td>
</tr>
<tr>
<td>Hypertension, n (%)</td>
<td>15 (75%)</td>
<td>13 (65%)</td>
<td>13 (43.3%)</td>
<td>0.124</td>
</tr>
<tr>
<td>Systolic blood pressure, mmHg</td>
<td>130 ± 15</td>
<td>131 ± 12</td>
<td>128 ± 14</td>
<td>0.662</td>
</tr>
<tr>
<td>Diastolic blood pressure, mmHg</td>
<td>78 ± 12</td>
<td>79 ± 10</td>
<td>79 ± 8</td>
<td>0.963</td>
</tr>
<tr>
<td>Diabetes mellitus, n (%)</td>
<td>2 (10%)</td>
<td>4 (20%)</td>
<td>1 (3.3%)</td>
<td>0.210</td>
</tr>
<tr>
<td>Atrial fibrillation, n (%)</td>
<td>10 (50%)</td>
<td>13 (65%)</td>
<td>13 (43.3%)</td>
<td>0.424</td>
</tr>
<tr>
<td>Myocardial infarction, n (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
</tbody>
</table>

Data are expressed as the mean ± SD, or number of patients (percentage) as appropriate. M indicates male; F, female; and NA, not applicable.
Correlations between DSCT measurements and MR severity: Strong correlations were found between some parameters of the mitral apparatus and MR severity: annular area \((r = 0.797, P < 0.001)\), tenting area at the central level \((r = 0.736, P < 0.001)\), anteroposterior diameter \((r = 0.733, P < 0.001)\), annular circumference \((r = 0.705, P < 0.001)\), intercommmissural diameter \((r = 0.691, P < 0.001)\), the distance between PM bases in systole \((r = 0.680, P < 0.001)\) and the distance between the heads of papillary muscles \((r = 0.654, P < 0.001)\) in systole; \(r = 0.662, P < 0.001\) in diastole). According to the multivariate regression analysis (Table V), mitral annular area \((P = 0.002)\) and tenting area at the central level \((P = 0.012)\) were significant determinants of MR severity.

**Discussion**

Due to the superiority of DSCT/MICT, such as the high resolution and high-contrast between the cardiac chamber wall and blood flow, this imaging modality has been confirmed to be a feasible tool to visualize the complex anatomical structure...
of heart valves and assess abnormalities.\textsuperscript{13-18} DSCT could be very helpful for patients who were difficult to assess with echocardiography due to a limited acoustic window. The results of our study indicated that DSCT could provide a quantitative and detailed analysis of the mitral apparatus.

As an important component of the mitral apparatus, the change in mitral annular geometry is known to be a cause and also a consequence of MR. However, the determinants of MR severity have not yet been fully elucidated. The mitral annulus has been clarified to be a non-planar “saddle” shape with lower remodeling in moderate to severe MR patients. Among patients with moderate to severe MR, the sphericity index and the distance between PM heads increased significantly, reflecting that displacement of the PMs was more obvious in the lateral view; the distance between the PM line and mitral annulus plane were greater, combined with an increased tenting height and area, indicating an apical displacement of the PMs. Moreover, the tenting area at the central level progressively increased while MR worsened, and the posterior leaflet angle at the central level was significantly larger in the moderate to severe group. These data showed the predominant tenting influence at the central part of the leaflets, leading to asymmetric leaflet tethering. Our findings are consistent with previous studies.\textsuperscript{27,28} Delgado, et al\textsuperscript{27} demonstrated a more noticeable leaflet tethering at the central and posteromedial levels in HF patients with moderate to severe MR, and an increased tenting height at the central level was a strong determinant of MR severity. Kwan, et al\textsuperscript{28} showed that the tenting area in the medial plane was the strongest determinant of MR severity, in ischemic and no-

Although a number of clinical studies have discussed alterations in the mitral annulus and leaflets, LV dilation accompanied by asymmetric PM displacement and leaflet tethering have not been well explored in nonischemic MR. With displacement of the papillary muscles (PM), enlargement and dysfunction of LV may result in a tethering change in the leaflets,\textsuperscript{26} which affected the dynamics and function of the mitral valve. In our study, the LV and mitral valve showed significant remodeling in moderate to severe MR patients. Among patients with moderate to severe MR, the sphericity index and the distance between PM heads increased significantly, reflecting that displacement of the PMs was more obvious in the lateral view; the distance between the PM line and mitral annulus plane were greater, combined with an increased tenting height and area, indicating an apical displacement of the PMs. Moreover, the tenting area at the central level progressively increased while MR worsened, and the posterior leaflet angle at the central level was significantly larger in the moderate to severe group. These data showed the predominant tenting influence at the central part of the leaflets, leading to asymmetric leaflet tethering. Our findings are consistent with previous studies.\textsuperscript{27,28} Delgado, et al\textsuperscript{27} demonstrated a more noticeable leaflet tethering at the central and posteromedial levels in HF patients with moderate to severe MR, and an increased tenting height at the central level was a strong determinant of MR severity. Kwan, et al\textsuperscript{28} showed that the tenting area in the medial plane was the strongest determinant of MR severity, in ischemic and no-

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### Table IV. Morphology and Cardiac Function Parameters of the Left Ventricle Were Compared Among the Study Groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Group 1 (n = 20)</th>
<th>Group 2 (n = 20)</th>
<th>Group 3 (n = 30)</th>
<th>P for ANOVA</th>
<th>1 versus 2</th>
<th>2 versus 3</th>
<th>1 versus 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV short axis length in systole, cm/m²</td>
<td>2.03 ± 0.26</td>
<td>2.13 ± 0.33</td>
<td>2.84 ± 0.63</td>
<td>&lt; 0.001</td>
<td>0.474</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV long axis length in diastole, cm/m²</td>
<td>2.72 ± 0.28</td>
<td>2.80 ± 0.37</td>
<td>3.56 ± 0.56</td>
<td>&lt; 0.001</td>
<td>0.506</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV long axis length in systole, cm/m²</td>
<td>3.85 ± 0.41</td>
<td>3.99 ± 0.55</td>
<td>4.76 ± 0.75</td>
<td>&lt; 0.001</td>
<td>0.467</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV long axis length in diastole, cm/m²</td>
<td>4.69 ± 0.27</td>
<td>4.70 ± 0.59</td>
<td>5.57 ± 0.78</td>
<td>&lt; 0.001</td>
<td>0.974</td>
<td>0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV sphericity index in systole</td>
<td>0.53 ± 0.05</td>
<td>0.53 ± 0.06</td>
<td>0.59 ± 0.07</td>
<td>&lt; 0.001</td>
<td>0.777</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>LV sphericity index in diastole</td>
<td>0.58 ± 0.05</td>
<td>0.60 ± 0.07</td>
<td>0.63 ± 0.06</td>
<td>&lt; 0.001</td>
<td>0.296</td>
<td>0.057</td>
<td>0.003</td>
</tr>
<tr>
<td>LV-EDV, mL/m²</td>
<td>63.21 ± 7.92</td>
<td>66.30 ± 10.42</td>
<td>105.56 ± 43.08</td>
<td>&lt; 0.001</td>
<td>0.611</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV-ESV, mL/m²</td>
<td>20.69 ± 4.12</td>
<td>23.04 ± 7.55</td>
<td>50.89 ± 32.81</td>
<td>&lt; 0.001</td>
<td>0.540</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV-EF, %</td>
<td>65.94 ± 5.56</td>
<td>64.49 ± 6.19</td>
<td>55.12 ± 12.45</td>
<td>&lt; 0.001</td>
<td>0.683</td>
<td>0.001</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Data are expressed as the mean ± SD. Group 1 indicates controls; Group 2, mild MR; Group 3, moderate to severe MR; LV, left ventricular; LV-EDV, left ventricular end-diastole volume; LV-ESV, left ventricular end-systole volume; and LV-EF, left ventricular ejection fraction.

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### Table V. Univariate and Multivariate Regression Analyses for Determinants of MR Severity (vena contracta width)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Univariate</th>
<th>Multivariate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>P</td>
</tr>
<tr>
<td>Annular area</td>
<td>0.838</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Annular circumference</td>
<td>0.778</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>A-P D</td>
<td>0.800</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>C-C D</td>
<td>0.764</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Tenting area at the central level</td>
<td>0.754</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>D-PM index in diastole</td>
<td>0.709</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV short axis length in systole</td>
<td>0.636</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>LV short axis length in diastole</td>
<td>0.721</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

A-P D indicates anteroposterior diameter; C-C D, intercommissural diameter; D-PM, distance between the heads of the papillary muscles; and NA, not applicable. LV short axis length was defined as the distance between the bases of the papillary muscles.
nischemic cardiomyopathies.

In severe MR, the effect of drug therapy is very limited, which is aimed at stabilizing hemodynamics for preoperative preparation.22 There are two main types of surgery used for correcting mitral regurgitation: MV repair and MV replacement. A multivariate analysis19–21 demonstrated that, compared to MV replacement, MV repair has obvious advantages, such as preserving LV function, avoiding long-term oral anticoagulation, reducing the incidence of postoperative complications, and improving survival.22–26 Recently, great progress has been made in new transcatheter technology. Detailed information and a comprehensive understanding of the geometry of the mitral apparatus is vitally important for MR treatment, especially MV repair. Evaluating the tethering of the mitral leaflet can contribute to predicting the prognosis.31 Dual-source CT can effectively evaluate the geometry of the mitral valve complex and left ventricle, providing comprehensive information for valvular treatment.

**Study limitations:** Our study has several limitations. First, the study sample was small. Furthermore, not all the moderate to severe MR patients underwent surgical treatment. We did not have enough surgical data to use as an independent standard to compare with the DSCT analysis. Third, the radiation risk still needs to be considered. Therefore, future DSCT/MDCT studies with larger patient cohorts that are compared with 3-dimensional echocardiography results are required to provide more insight into mitral apparatus alteration.

**Conclusions:** The differences in mitral valve geometry between MR patients and normal controls are significant. In patients with moderate to severe MR, dilatation of the mitral annulus was more significant in the anteroposterior direction, while a more prominent tethering of the mitral leaflets at the central level was observed. The mitral annular area and tenting area at the central level were the strongest determinants of MR severity. DSCT is available to quantitatively assess mitral valve morphology, which can provide information regarding MR geometry.

**DISCLOSURE**

The authors declare that they have no conflict of interest.

**REFERENCES**


