Mechanisms of Recurrent Functional Mitral Regurgitation After Mitral Valve Repair in Nonischemic Dilated Cardiomyopathy

Importance of Distal Anterior Leaflet Tethering

Alex Pui-Wai Lee, MB, ChB; Michael Acker, MD; Spencer H. Kubo, MD; Steven F. Bolling, MD; Seung W. Park, MD; Charles J. Bruce, MD; Jae K. Oh, MD

Background—Recurrent functional mitral regurgitation (MR) has been reported after mitral valve repair with annuloplasty in patients with dilated cardiomyopathy, but the mechanism is not understood completely. The authors sought to identify abnormalities of the mitral valve and left ventricle that are associated with recurrent MR after mitral annuloplasty.

Method and Results—In 104 patients with idiopathic dilated cardiomyopathy who underwent annuloplasty for functional MR, basal mitral anterior leaflet angle, distal mitral anterior leaflet angle (ALAtip), posterior leaflet angle, coaptation depth, tenting area, mitral annular dimensions, left ventricular volumes, and MR severity were quantified by echocardiography before surgery and at 6-month intervals after it. Compared with patients without MR recurrence (n=79), patients with recurrent MR (defined as ≥2+) (n=25) had greater ALAtip (P<0.001) and basal mitral anterior leaflet angle (P<0.001), greater coaptation depth and tenting area (P<0.001), larger left ventricular volumes (P<0.001), and worse left ventricular ejection fraction (P<0.05) but similar mitral annular dimensions and postoperative exaggeration in posterior leaflet angle. Multivariable analysis identified postoperative ALAtip as the major determinant of postoperative MR. Receiver operator characteristic curves identified preoperative ALAtip as the best predictor of MR recurrence (area under curve, 0.98). For ALAtip >25°, the sensitivity, specificity, and positive and negative predictive values in predicting recurrent MR were 88%, 94%, 82%, and 93%, respectively. Three distinct patterns of anterior leaflet tethering (minimal, basal, and distal) with an increasing risk of recurrent MR were identified.

Conclusions—Posterior leaflet tethering is invariable after mitral annuloplasty, rendering postoperative mitral competence highly dependent on distal anterior leaflet mobility. (Circulation. 2009;119:2606-2614.)

Key Words: cardiomyopathy ■ mitral valve ■ regurgitation ■ surgery ■ ventricles

Functional mitral regurgitation (MR) is commonly observed in patients with dilated cardiomyopathy (DCM) and is associated with poor clinical outcomes. The primary mechanisms of functional MR involve mitral annular dilation and mitral leaflet restriction secondary to left ventricular (LV) remodeling. Although studies have shown that mitral valve repair—specifically, mitral ring annuloplasty—is associated with improvement of cardiac performance and heart failure symptoms, postoperative recurrence of MR was not uncommon and was associated with progressive LV remodeling that carried a grave prognosis.

Clinical Perspective on p 2614

In sheep studies, mitral ring annuloplasty markedly reduced the mobility of the posterior leaflet (PL) without affecting the anterior leaflet (AL), such that valve closure became essentially a single-AL process, with the frozen PL serving only as a buttress for closure. Nevertheless, recent retrospective clinical studies have suggested that restricted PL mobility, rather than AL motion, was the predominate contributor to recurrent ischemic MR after annuloplasty. In these studies, AL mobility was quantified by measuring the tethering angle at the basal portion of the leaflet (Figure 1). However, the anatomy of chordae insertion at the AL is distinct and complex. It consists of both fine marginal chordae that insert the leaflet tip to prevent prolapse and thicker basal (or strut) chordae that insert closer to the leaflet base. Clinical observations have suggested that, with increased tethering, the basal AL becomes tented and nearly fixed by these basal chordae; however, the more distal AL can be less restricted and pivot around the “knee” where these chordae attach. Hence, measuring the tethering angle of...
the basal AL may not fully account for the mobility of the whole leaflet.

In the present study, we sought to define the mechanisms of recurrent MR after annuloplasty for functional MR complicating DCM. On the basis of the anatomy of the mitral apparatus, we hypothesized that postannuloplasty mitral valve competence is predominantly dependent on AL mobility and that the tethering of the distal AL is a better descriptor of overall AL mobility, which can accurately predict recurrence of functional MR after annuloplasty.

**Methods**

**Subjects**

The Acorn trial was a prospective, randomized, unblinded evaluation of a cardiac support device (CSD) (CorCap CSD; Acorn Cardiovascular Inc, St Paul, Minn) in patients with DCM. Patients were eligible for the trial if they had New York Heart Association class II to IV heart failure, were aged 18 to 80 years, and had LV ejection fraction <45%, LV end-diastolic dimension >6 cm, and 6-minute walk distance <450 m. Patients were enrolled into the mitral valve surgery stratum (n=193) if they required mitral valve surgery because of severe MR (grade ≥3+). They were randomly assigned to mitral valve surgery plus CSD or mitral valve surgery alone. Most patients were on optimal medical therapy at entry, assigned to mitral valve surgery plus CSD or mitral valve surgery alone. Most patients were on optimal medical therapy at entry, assigned to mitral valve surgery plus CSD or mitral valve surgery alone. Most patients were on optimal medical therapy at entry, assigned to mitral valve surgery plus CSD or mitral valve surgery alone.

Nine of the 193 patients did not undergo mitral valve surgery (5 refused, 1 died before surgery, and it was surgically decided for 3 patients). The degree of residual MR was monitored by intraoperative transesophageal echocardiography. If a residual MR of grade 0/1+ could not be achieved with mitral valve repair or if the surgeons anticipated poor results with repair (because of heavily calcified valves, for example), the valve was replaced. Most patients (n=155; 84.2%) received a mitral annuloplasty ring, but 29 (15.8%) underwent mitral valve replacement. Of these 155 patients with annuloplasty, the majority (n=117) had idiopathic DCM and were analyzed in the present study. Patients with ischemic and valvular causes of heart failure were excluded from this analysis. Among the 117 patients with idiopathic DCM, 25 patients developed recurrent MR grade ≥2+ at 6 months, whereas the remaining 92 patients had postoperative MR grade ≤1+ during the 18-month follow-up. All of the 25 patients with recurrent MR had optimal images of the basal chordae that allowed adequate assessment of leaflet tethering. Of the 92 patients with no significant MR recurrence, 13 were excluded from this analysis because the basal chordae were not adequately visualized such that basal and distal AL tethering could not be measured confidently. In the final analysis, 25 patients who had postoperative recurrent MR grade ≥2+ (MR+ group) were compared with 79 patients who had recurrent MR grade ≤1+ (MR− group).

**Surgical Techniques**

Twenty-nine surgical centers participated in the study. Mitral annuloplasty was performed with standard operative techniques, including cardiopulmonary bypass and undersized annuloplasty ring placement. CorCap CSD implant techniques have been described previously. The key of implantation was to obtain a conformal fit with the CSD evenly distributed around the heart without any folds and with an even “tent” test in which the CSD is lifted off the heart with a forceps and then returns to a smooth fit within 1 to 2 heartbeats. Care was taken to make sure that the LV end-diastolic dimension was not reduced by >10% compared with baseline. This implant technique would minimize uneven tension around the LV and mitral annulus.

**Echocardiography**

Transthoracic echocardiography was performed within a week before surgery and at 6-month intervals postoperatively. Measurements of LV dimensions and MR severity were made by the Acorn trial Echo Core Laboratory (Mayo Clinic, Rochester, Minn). Measurement of mitral valve parameters was made separately by 1 of the investigators (A.P.L.). The preoperative and the 6-month postoperative studies (the earliest time of MR recurrence) of the MR+ group were compared with those of the MR− group.

**Assessment of MR and LV Geometry**

Quantitative assessment of MR severity was made by measuring the vena contracta width (VCW) of the regurgitant jet, which was defined as the narrowest portion of the jet that occurs at the orifice or just downstream from it. VCW was measured in the parasternal long-axis view in at least 3 cardiac cycles and was then averaged. MR recurrence was considered clinically significant for postoperative VCW ≥0.30 cm ≥2+ at 6 months. Severe (4+) MR was defined as VCW ≥0.70 cm. Quantitative parameters of effective regurgitation orifice area and regurgitation volume were measured to subclassify moderate regurgitation into grade 2±3± according to the recommendation of the American Society of Echocardiography. Supportive parameters including jet area, continuous-wave Doppler jet profile, pulse wave Doppler transmitral flow, and pulmonary venous flow were examined as an integrative approach to evaluation of MR severity. The LV end-diastolic volume (LVEDV), LV end-systolic volume (LVESV), and EF were measured with the modified biplane Simpson method. The LV sphericity index was calculated by dividing the LV end-systolic short-axis dimension by the long-axis dimension in the 4-chamber view.

**Mitral Valve Configuration**

Detailed evaluation of the mitral valve configuration was performed in midsystole in the parasternal long-axis view (Figure 1). The tenting area was measured as the area enclosed by the mitral leaflets and the annular plane. The coaptation length was measured as the length of systolic leaflet contact. The coaptation depth was defined as the shortest distance between the coaptation and the annular plane. Mitral annular diameters were measured in the parasternal long-axis, 4-chamber, and 2-chamber views, from which mitral annular area was calculated. The tethering of basal AL was assessed by measuring the angle between the annular plane and a line that joins the anterior...
annulus and coaptation point (distal anterior leaflet angle [ALA\textsubscript{tip}]). The mobility of PL was assessed by the angle between the annular plane and PL (PLA). To ensure accurate assessment of basal and distal AL tethering, the attachment of basal chordae to the body of AL had to be clearly visualized. Because detailed evaluation of mitral leaflet tethering was not the initial focus of the Acorn trial, the basal chordae were not adequately imaged in 13 cases because of suboptimal gain setting or imaging focus, and those cases were excluded from analysis.

**Statistical Analysis**

Data were analyzed with the use of statistical software (SPSS for Windows, version 11.5.1; SPSS Inc, Chicago, Ill). Normality of continuous data was analyzed with the Kolmogorov-Smirnov test. All continuous variables except postoperative VCW and ring size were normally distributed. Results were expressed as mean±SD, median and range, or number of patients (percentage) as appropriate. For within-group comparisons before and after annuloplasty, paired \(t\) test or Wilcoxon signed rank test was used. Between-group differences were assessed by unpaired \(t\) test, Mann-Whitney \(U\) test, or Pearson \(r\) test. Correlations between normally distributed variables were tested by Pearson coefficient. Correlations of postoperative VCW with other variables were tested by Spearman coefficient. Multivariable logistic regression with the forward stepwise method was performed to identify preoperative predictors of significant MR recurrence (\(\geq 2+\)) at 6 months. The predictors tested were age, gender, CSD implantation, ring size and types, preoperative systolic and diastolic blood pressures, LVEDV, LVESV, LVEF, sphericity index, tenting area, coaptation depth, coaptation length, mitral annular area, ALAtip, ALA\textsubscript{base}, and PLA. These factors were previously reported to be associated with MR recurrence after mitral valve repair\textsuperscript{11–13} Forward stepwise logistic regression was then performed on postoperative variables to identify factors responsible for significant MR recurrence. For this analysis, postoperative systolic and diastolic blood pressures, medications, LVEDV, LVESV, LVEF, sphericity index, tenting area, coaptation depth, coaptation length, mitral annular area, ALAtip, ALA\textsubscript{base}, and PLA at 6 months were tested.\textsuperscript{11–13} Diagnostic performances of preoperative echocardiographic parameters in predicting significant MR recurrence were determined with receiver operating characteristic curves. A \(P\) value of \(P<0.05\) was considered statistically significant.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscipt as written.

**Results**

**Patient Characteristics**

No differences were found in age, gender, blood pressures, heart rate, comorbidities, preoperative functional class, ring size and types, postoperative medications, and the proportions of patients with CSD implantation between the 2 groups (Table 1). No death occurred before the follow-up at 6 months. Three (3.8%) and 1 (4%) death occurred between 6 and 12 months in the MR\textsuperscript{−} and MR\textsuperscript{+} groups, respectively (\(P=0.96\)). Compared with the MR\textsuperscript{−} group, the MR\textsuperscript{+} group had higher postoperative New York Heart Association class (\(P=0.01\)) and showed a trend toward higher preoperative MR grade (\(\geq 2+\)) (92% versus 78%; \(P=0.05\)).

**Changes in LV Geometry and Mitral Valve Configuration After Annuloplasty**

As the definition implies, a significantly greater decrease in VCW (\(P<0.001\)) occurred in the MR\textsuperscript{−} group compared with the MR\textsuperscript{+} group (Table 2). Preoperative LVEDV (\(P<0.001\)) and LVESV (\(P<0.001\)) were significantly greater in the MR\textsuperscript{+} group. No intergroup differences were found in preoperative LVEF and sphericity index. After annuloplasty, a significant reduction of LVEDV (\(P<0.001\)) and LVESV (\(P<0.001\)) and a significant increase in sphericity index (\(P<0.001\)) occurred in the MR\textsuperscript{−} group. However, in the MR\textsuperscript{+} group, these parameters were unimproved. Furthermore, LVEF was stable in the MR\textsuperscript{−} group but deteriorated in the MR\textsuperscript{+} group (\(P<0.05\)).

Compared with the MR\textsuperscript{−} group, the MR\textsuperscript{+} group had greater preoperative ALAtip (\(P<0.001\)), ALA\textsubscript{base} (\(P<0.001\)), PLA (\(P=0.002\)), coaptation depth (\(P<0.001\)), tenting area (\(P<0.001\)), and VCW (\(P=0.03\)) (Table 2). No significant preoperative intergroup differences were found in the mitral annular area and coaptation length.

After annuloplasty, the ALA\textsubscript{base} and ALAtip were significantly reduced in the MR\textsuperscript{−} group (\(P<0.001\)) but were unchanged in the MR\textsuperscript{+} group. Conversely, for both groups, PLA increased significantly (\(P<0.001\)) to the same extent (between-group \(P=0.39\)); mitral annular area was significantly decreased (\(P<0.001\)) in both groups to a similar extent (between-group \(P=0.65\)); and coaptation depth and tenting area decreased (\(P<0.001\)) but to a greater extent in the MR\textsuperscript{−} group (between-group \(P<0.001\)).

Preoperatively, LVEDV correlated significantly with ALAtip (\(r=0.41, P<0.001\)), ALA\textsubscript{base} (\(r=0.30, P=0.004\)), PLA (\(r=0.34, P=0.001\)), and tenting area (\(r=0.57, P<0.001\)). After annuloplasty, LVEDV also correlated significantly with ALAtip (\(r=0.54, P<0.001\)), ALA\textsubscript{base} (\(r=0.51, P=0.004\)), and tenting area (\(r=0.60, P<0.001\)) but not with PLA (\(r=0.08, P=0.45\)).

**Predictors and Mechanisms of Recurrent MR**

Preoperative ALAtip correlated strongly (\(P=0.66, P<0.001\)) with postoperative VCW. Preoperative ALA\textsubscript{base} (\(P=0.44, P<0.001\)), coaptation depth (\(P=0.47, P<0.001\)), tenting area (\(P=0.36, P<0.001\)), VCW (\(P=0.35, P=0.001\)), LVEDV (\(P=0.38, P<0.001\)), LVESV \(P=0.33, P=0.002\), and LVEF (\(P=0.22, P=0.04\)) had moderate correlation with postoperative VCW. Other preoperative variables including PLA, coaptation length, mitral annular area, sphericity index, blood pressures, CSD, ring size and types, gender, and age did not correlate significantly with postoperative VCW. Several preoperative predictors for significant MR recurrence were identified on univariable analysis: preoperative VCW, coaptation depth, tenting area, ALAtip, ALA\textsubscript{base}, PLA, LVEDV, and LVESV (\(P<0.05\) for all). Only preoperative ALAtip (odds ratio = 1.74; 95% confidence interval [CI], 1.28 to 2.36; \(P<0.001\)) and preoperative LVEDV (odds ratio = 1.02; 95% CI, 1.01 to 1.04; \(P=0.04\)) were independently predictive of significant MR recurrence on multivariable analysis.

On receiver operating characteristic curves, the best preoperative predictor of significant MR recurrence was preoperative ALAtip, followed by coaptation depth and ALA\textsubscript{base} (Figure 2). Preoperative VCW had modest diagnostic performance (area under curve = 0.66; 95% CI, 0.54 to 0.77; \(P=0.03\)). The cutoff value of preoperative ALAtip of >25° in predicting recurrent MR had sensitivity, specificity, and positive and negative predictive values of 88%, 94%, 82%, and 93%, respectively. Similar diagnostic performance of
Table 1. Clinical and Group Characteristics

<table>
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<th>Characteristic</th>
<th>MR− Group (n=79)</th>
<th>MR+ Group (n=25)</th>
<th>χ²</th>
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<td>24 (30)</td>
<td>8 (32)</td>
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<tr>
<td>4+</td>
<td>18 (23)</td>
<td>12 (48)</td>
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<td>1+</td>
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<td>2+</td>
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<td>12 (48)</td>
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<tr>
<td>3+</td>
<td>0</td>
<td>10 (40)</td>
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<td>4+</td>
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<td>Diastolic blood pressure, mm Hg</td>
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<td>74±12</td>
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<td>Postoperative</td>
<td>74±14</td>
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<tr>
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<td>21 (84)</td>
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<td>23 (92)</td>
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<td>0.94</td>
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<td>21 (84)</td>
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<td>β-Blocker</td>
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<td>Spironolactone</td>
<td>34 (43)</td>
<td>9 (36)</td>
<td>0.39</td>
<td>0.53</td>
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</table>

NYHA indicates New York Heart Association; ACEI, angiotensin-converting enzyme inhibitor; and ARB, angiotensin receptor blocker. Data are expressed as mean±SD, median and range, or number of patients (percentage) as appropriate.
ALAtip was found in subgroups with (area under curve
\(0.98;\) 95% CI, 0.95 to 1.0; \(P=0.001\)) or without (area under
curve \(0.98;\) 95% CI, 0.93 to 1.00; \(P=0.001\)) CSD
implantation.

Postoperative ALAtip correlated strongly (\(r=0.75, P<0.001\))
with postoperative VCW (Figure 3). The former also correlated
inversely with postoperative coaptation length (\(r=-0.60, P<0.001\)),
which in turn correlated inversely with postoperative
VCW (\(r=-0.73, P<0.001\)). Other postoperative variables that
correlated with postoperative VCW were postoperative coapta-
tion depth (\(r=0.70, P<0.001\)), tenting area (\(r=0.61, P<0.001\)),
LVEDV (\(r=0.54, P<0.001\)), LVESV (\(r=0.55, P<0.001\)),
and LVEF (\(r=-0.40, P<0.001\)). Postoperative mitral annu-
lar area, sphericity index, medications, and blood pressures
did not correlate significantly with postoperative VCW. On
univariable analysis, postoperative predictors of significant
MR recurrence included coaptation depth, tenting area, co-
aptation length, ALAtip, ALA base, LVESV, LVEDV, and
LVEF (\(P<0.05\) for all). Multivariable analysis identified
postoperative ALAtip (odds ratio 1.75; 95% CI, 1.25 to 2.44;
\(P=0.001\)) as the only independent factor associated with
significant MR recurrence.

**Patterns of AL Tethering**

Preoperative basal chordae tethering was associated with AL
bend during systole that could be recognized readily by

<table>
<thead>
<tr>
<th>Table 2. Preoperative and Postoperative Echocardiographic Parameters</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>----------------</td>
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<tr>
<td>VCW, cm</td>
</tr>
<tr>
<td>LVEDV, mL</td>
</tr>
<tr>
<td>LVESV, mL</td>
</tr>
<tr>
<td>LVEF, %</td>
</tr>
<tr>
<td>Sphericity index</td>
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<tr>
<td>Coaptation length, cm</td>
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<tr>
<td>Coaptation depth, cm</td>
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<tr>
<td>Tenting area, cm²</td>
</tr>
<tr>
<td>Mitral annular area, cm²</td>
</tr>
<tr>
<td>ALA base °</td>
</tr>
<tr>
<td>ALAtip °</td>
</tr>
<tr>
<td>PLA °</td>
</tr>
</tbody>
</table>

*\(P<0.001\) compared with preoperative value.
†\(P<0.05\) compared with MR− group.
‡\(P<0.001\) compared with MR+ group.
§\(P<0.05\) compared with preoperative value.

ALA base was found in subgroups with (area under curve = 0.98;
95% CI, 0.95 to 1.0; \(P<0.001\)) or without (area under
curve = 0.98; 95% CI, 0.93 to 1.00; \(P<0.001\)) CSD
implantation.

Postoperative ALA base correlated strongly (\(r=0.75, P<0.001\))
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correlated with postoperative VCW were postoperative coapta-
tion depth (\(r=0.70, P<0.001\)), tenting area (\(r=0.61, P<0.001\)),
ALA base (\(r=0.60, P<0.001\)), PLA (\(r=-0.24, P=0.02\)),
LVEDV (\(r=0.54, P<0.001\)), LVESV (\(r=0.55, P<0.001\)),
and LVEF (\(r=-0.40, P<0.001\)). Postoperative mitral annu-
lar area, sphericity index, medications, and blood pressures
did not correlate significantly with postoperative VCW. On
univariable analysis, postoperative predictors of significant
MR recurrence included coaptation depth, tenting area, co-
aptation length, ALA base, ALAtip, LVESV, LVEDV, and
LVEF (\(P<0.05\) for all). Multivariable analysis identified
postoperative ALA base (odds ratio = 1.75; 95% CI, 1.25 to 2.44;
\(P=0.001\)) as the only independent factor associated with
significant MR recurrence.

**Figure 2.** Receiver operating characteristic curves of preoperative ALA base (A), ALAtip (B), PLA (C), and coaptation depth (D) in predicting recurrent MR. AUC indicates area under curve.
echocardiography (Figure 4). The appearance of AL bend was more frequently observed in the MR+ group than in the MR− group (96% versus 78%; χ² = 4.07; P = 0.04) (Figure 5). In patients with AL bend, ALA₉₀ was significantly greater than ALA₅₀ (42±10° versus 21±8°; P < 0.001). Of the 18 patients without AL bend, 17 had an ALA₅₀ <25° and did not have recurrent MR (11 of them had no detectable MR at 6 months). The sensitivity and specificity of the preoperative AL bend appearance in predicting recurrent MR of grade ≥2+ were 96% and 22%, respectively.

On the basis of preoperative AL shape, 3 types of AL tethering patterns with relevance to the likelihood of postoperative MR recurrence could be recognized (Figure 6). Type I (minimal AL tethering) was characterized by small ALA₉₀ and ALA₅₀ (both ≤25°) with minimal AL bend; type II (predominant basal AL tethering) was characterized by a prominent AL bend with a large ALA₉₀ (>25°) but a small ALA₅₀ (≤25°); and type III (distal AL tethering) was characterized by an increase in both ALA₉₀ and ALA₅₀ (both >25°) and, usually, an AL bend of milder degree. The numbers of patients with type I, II, and III tethering patterns were 22 (21%), 57 (55%), and 25 (24%), respectively. The proportions of patients who had recurrent MR in these type I, II, and III patterns were 0% (0 of 22), 5% (3 of 57), and 88% (22 of 25), respectively (χ² = 74.0; P < 0.001).

**Discussion**

The present study provides the first demonstration that tethering of the distal AL secondary to LV dilatation is the primary mechanism of recurrent MR after mitral annuloplasty in idiopathic DCM complicated by functional MR. This study identified preoperative ALA₅₀ >25° as the best preoperative predictor of recurrent MR. Furthermore, the study suggests a novel classification of AL tethering pattern based on the anatomy of chordal insertion and with important clinical implications on the likelihood of postoperative recurrent MR.

**Anatomy of AL Tethering**

The normal chordae system of mitral valve (Figure 7) consists of marginal chordae that attach to the free edges of both leaflets and 2 thicker basal chordae that insert along each half of the ventricular surface of the basal AL, providing additional support. As a result of the separate sites of chordal insertion, the differential tethering effect on the basal and distal portions of AL varies according to the predominant direction of the tethering forces. We postulated that, with predominant posterior displacement of the papillary muscles,
tethering of the basal chordae is more severe because these chordae insert into the basal AL, which is farther away from the papillary muscles than the distal AL. The distal portion of the AL is less restricted and often overrides the restricted PL, determining the AL bend shape. If apical displacement is predominant, both leaflets are tethered apically, and a restricted motion of the distal AL is also seen. Indeed, Agricola et al\(^2\) described 2 patterns of leaflet tethering based on the effect of tethering direction on the symmetry of leaflet restriction. Because of these anatomic considerations, description of AL tethering should consider the tethering effects on both basal and distal AL exerted by the basal and marginal chordae, respectively. By measuring only the basal AL tethering angle, previous studies\(^1\)–\(^3\) did not specifically address the mobility of the distal AL, and its relation with postoperative MR might have been overlooked.

In the present study, the mobility of distal AL was assessed by measuring the AL\(_{\text{tip}}\). In fact, the AL\(_{\text{tip}}\) represents a measurement that reflects the net tethering effect of the whole AL as the angle increases with tethering of the distal as well as the basal portions of the leaflet. Our findings indicated that measurement of AL\(_{\text{tip}}\) provides more comprehensive information on AL mobility, with important implications for predicting sustained surgical success after annuloplasty.

Mechanisms and Predictors of Recurrent MR

Competent closure of the mitral valve requires a large area of coaptation between leaflets that allows high-friction resistance to abnormal valve movement. With markedly restricted PL mobility after annuloplasty, adequate coaptation requires the AL to be sufficiently mobile.\(^1\) The present study demonstrated that the most distinct feature of a regurgitant mitral valve after annuloplasty is the tethering of distal AL. Furthermore, residual MR after surgery could be associated with continued LV remodeling and begets more MR.\(^8\) In contrast, exaggerated PL tethering was observed in most patients postoperatively. Because annuloplasty per se does not alter AL tethering, postoperative distal AL tethering can largely be predicted from preoperative echocardiography. This observation explains the excellent predictive accuracy of the preoperative AL\(_{\text{tip}}\).

Patterns of AL Tethering

Three distinct types of AL tethering pattern can be readily recognized on echocardiography (Figure 6). In type I, the AL is minimally tethered along its entire length. The rapid visual clues on echocardiography for this type of tethering are a small AL\(_{\text{tip}}\) with minimal AL bend. Theoretically, it is possible to see a “straight” AL with severe apical tethering of both basal and distal AL. In practice, this appearance is unusual, probably because a posterior component is almost always present in the tethering vector as the chordae insert into the AL obliquely from the papillary muscles, which are posterior structures (Figure 7). Indeed, all except 1 of this study’s 18 patients without AL bend had a small AL\(_{\text{tip}}\) (ie, type I minimal tethering) and did not have recurrent MR.

Type II represents basal chordae, posteriorly directed tethering and is characterized by a prominent AL bend on echocardiography. Type III represents severe apical tethering
of both basal and distal AL and is recognizable by the large ALAtip with a variable, but usually milder, degree of AL bend. In general, patients with types I and II AL tethering have a good chance of sustained success in mitral annuloplasty, whereas patients with type III are at high risk of MR recurrence.

Comparison With Previous Studies
Calafiore et al\textsuperscript{21} showed in a study of 29 patients with DCM that a coaptation depth \( >1 \) cm was associated with higher-grade MR after repair. This result is consistent with our findings that 24 of the 25 patients in the MR+ group had a coaptation depth \( >1 \) cm. However, it should be recognized that coaptation depth is a parameter integrating many independent geometric factors, including AL tethering, PL tethering, mitral annular dimension, and the position of leaflet coaptation. Therefore, the coaptation depth is not a specific descriptor of the distal AL mobility. Indeed, 44\% (35 of 79) of the patients in the MR– group had a preoperative coaptation depth \( >1 \) cm (Figure 5D).

In a study of 30 patients with ischemic MR, Kuwahara et al\textsuperscript{12} suggested that exaggerated PL tethering made a predominant contribution to recurrent or persistent MR after annuloplasty. In addition, in a study of 51 patients, Magne et al\textsuperscript{13} found that a PL tethering angle of \( \geq 45^\circ \) was the best predictor of postoperative persistence of MR. These different observations may be explained by the fact the ALAtip was measured in the present study for a more precise description of distal AL tethering. Moreover, the degree of PLA was apparently greater in patients in this study than in those of prior studies. Therefore, it was probable that the mobility of AL had played an even more critical role in preventing recurrent MR in patients in this study.

Limitations
Because all patients had nonischemic DCM, the results may not be generalizable to ischemic MR, which may have different mechanisms. The study is retrospective, and 13 patients (11\%) were excluded because of inadequate visualization of the basal chordae. However, in our experience, secondary chordae were more easily visualized in the presence of significant basal leaflet tethering because of the obvious angulation in the AL body where the basal chordae attached. Indeed, inadequate images were only found in patients without significant MR recurrence. Therefore, any selection bias would have acted against our results. The CSD implantation in 61\% of patients might limit the generalizability of the findings to DCM patients undergoing annuloplasty without CSD. Nevertheless, multivariable analysis found no significant impact of CSD implantation on MR recurrence, and the diagnostic performance of preoperative ALAtip was excellent in subgroups with or without CSD. A standard protocol to look for and quantify residual MR at the time of surgery was not mandatory, and intraoperative volume load testing was not done routinely. A difference in the amount of MR in patients leaving the operation room could not be excluded. Yet, this is the standard practice among cardiovascular surgeons, and the preoperative MR severity in this study did not seem to be a significant factor for the findings on multivariable analysis.

Clinical Implications
On the basis of the results of this study, we recommend preoperative echocardiographic evaluation that focuses on the pattern and severity of AL tethering in patients with functional MR complicating idiopathic DCM who are undergoing mitral valve surgery. Rapid visual screening allows classification into type I AL configuration if AL bending is absent, in which case a good outcome of annuloplasty can be anticipated. However, the presence of AL bending does not preclude successful annuloplasty, and measurement of the ALAtip should be performed to distinguish between type II and III tethering. The success rate for repair is good in patients with type II but low in patients with type III. For the latter group, the better option may be mitral valve replacement, or other surgical approaches that target the tethering mechanisms may be considered.\textsuperscript{22} These new observations should help to select suitable candidates for annuloplasty and define new approaches to functional MR associated with DCM.

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References


**CLINICAL PERSPECTIVE**

Functional mitral regurgitation (MR) is a common complication of dilated cardiomyopathy and carries a poor prognosis. Although surgical restrictive mitral annuloplasty is often performed and has been shown to improve heart failure symptoms, recurrence of MR is not uncommon and is associated with increased morbidity and mortality. We performed a study investigating the mechanisms and predictors of recurrent MR in patients with idiopathic dilated cardiomyopathy who underwent mitral annuloplasty for functional MR in the Acorn trial. We comprehensively assessed the anatomy of the mitral apparatus and the left ventricle using echocardiography before surgery and at 6 months after it. The key finding of this study is that the preoperative tethering of the distal anterior mitral leaflet as a result of left ventricular dilatation is strongly predictive of recurrence of clinically significant MR after surgery. We observed that restrictive annuloplasty exaggerates tethering of the posterior leaflet, which renders postoperative mitral valve closure almost entirely dependent on the anterior leaflet. On receiver operating characteristic curve analysis, a preoperative distal anterior leaflet tethering angle of >25° had sensitivity, specificity, and positive and negative predictive values of 88%, 94%, 82%, and 93%, respectively. Three distinct tethering patterns of the anterior leaflet (minimal, basal, and distal) in association with increasing risk of postoperative MR recurrence were described. The results of this study may be useful to clinicians for selecting candidates of mitral valve repair and developing new surgical techniques in the management of patients with functional MR.
Mechanisms of Recurrent Functional Mitral Regurgitation After Mitral Valve Repair in Nonischemic Dilated Cardiomyopathy: Importance of Distal Anterior Leaflet Tethering
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