RING+STRING
Successful Repair Technique for Ischemic Mitral Regurgitation With Severe Leaflet Tethering

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Background—Residual/recurrent mitral valve regurgitation is observed in 30% after undersized ring annuloplasty (RING). RING addresses primarily annular dilatation but does not correct severe leaflet tethering attributable to papillary muscle (PM) displacement. We proposed adjunctive PM repositioning under transesophageal echocardiography (TEE) guidance in the loaded beating heart using a transventricular suture (STRING).

Methods and Results—Patients with tenting height ≥10 mm were identified as high-risk patients for repair failure. In these patients (n = 30, age 68 ± 11 years, ejection fraction 37 ± 14%), RING (partial, median 29 mm) was combined with the adjunctive STRING-technique. A Teflon-pledgeted 3-0-polytetrafluoroethylene-suture was anchored in the posterior PM via horizontal aortotomy, exteriorized through the aorto-mitral continuity, and tied in the loaded beating heart under TEE guidance. Tenting height (14 ± 2 mm versus 6 ± 1 mm, P < 0.001) and tenting area (3.9 ± 0.9 cm² versus 1.0 ± 0.2 cm², P < 0.001) decreased. The distance between pPM and aorto-mitral continuity decreased (44 ± 4 mm versus 37 ± 3 mm, P < 0.001). Survival at 2 years was similar compared with a historical matched control-group (89% versus 73%, P = 0.13), whereas freedom from MR > II was higher in the RING+STRING-group (94% versus 71%, P = 0.01). End-diastolic (61.7 ± 7.2 mm versus 54.8 ± 9.2 mm, P < 0.001) and end-systolic (48.5 ± 8.5 mm versus 42.7 ± 7.8 mm, P = 0.002) ventricular diameters decreased in the RING+STRING-group but persisted in the control-group (60.4 ± 7.8 mm versus 58.9 ± 7.5 mm, P = 0.38; 47.8 ± 9.6 mm versus 48.3 ± 9.5 mm, P = 0.52). During follow-up (median 26 months) only 1 patient of the study-group required reoperation for degenerative MR, while 2 control-group patients underwent reoperation for recurrent functional MR.

Conclusions—Our novel approach for IMR attenuates high risk of repair failure in patients with severe leaflet tethering and results in reverse remodeling. (Circulation. 2009;120[suppl 1]:S85–S91.)

Key Words: mitral valve ■ ischemic mitral regurgitation ■ mitral valve repair

Ischemic mitral regurgitation (IMR) is observed as frequent complication of myocardial infarction and is associated with a poor prognosis.1 The pathogenesis of IMR includes annular dilatation (Carpentier type I) in all cases. Some patients, however, also exhibit severe restrictive leaflet motion (Carpentier type IIIb) with severe leaflet tethering attributable to papillary muscle (PM) displacement.2 Although undersized ring annuloplasty (RING) as treatment of choice can correct both annular and subvalvular geometry, RING primarily addresses annular dilatation. Accordingly, most centers observe residual/recurrent MR in more than 30% of patients—particularly with the use of partial flexible rings.4–7 Better results have been achieved with the use of complete rigid or semirigid ring implants.8–10 Persistent leaflet tethering has been identified as mechanism of repair failure,6,7,11,12 unfortunately the degree of leaflet tethering has not been quantified in all other studies.

These failures of RING emphasize the necessity of a subvalvular solution beyond RING for this dilemma. Several adjunctive repair techniques have been proposed to correct this altered subvalvular geometry, but such techniques represent experimental work and none have received widespread clinical acceptance. Leaflet extension has been performed successfully, but there are no further clinical data beyond this case report.13 Borger et al recently reported initial results using cutting second-order chordae as adjunctive repair technique to RING14—the impact of dividing these second-order chordae on LV systolic function, however, has been discussed controversially.15,16 Kron et al proposed relocation of the displaced posterior papillary muscle (pPM) with a transventricular suture anchoring the pPM toward the mitral annulus as an adjunct to RING.17 Based on this report and the mechanistic insight reported by Tibayan et al,18 that the distance between the midseptal fibrous annulus and the pPM...
plays a key role in the pathogenesis of IMR, the direction of internal repositioning of the pPM was refined in a sheep model of acute IMR. Building on these data we have developed a new clinical adjunctive repair technique (Figure 1), which allows repositioning of the pPM under TEE guidance in the loaded beating heart. In the present investigation we report our initial experience with this new repair approach combining RING and pPM repositioning (ie, annular and subvalvular repair in comparison with a control-group derived retrospectively). All of these patients—both in study-group and control-group—had severe leaflet tethering with high risk of repair failure. To test our hypothesis that correcting the altered subvalvular geometry is of paramount importance, partial flexible ring implants were used in all patients. Thus the potential beneficial effect of a complete and rigid ring implant was intentionally avoided.

**Patients and Methods**

Ethics approval was granted by our local ethics committee. Indication for mitral valve repair was moderate-to-severe MR or more (≥MR III) associated with symptoms of heart failure (≥NYHA functional class II). Preoperative echocardiography was used to assess severity of MR and characterize the underlying mechanisms. Careful assessment of the underlying mechanisms was achieved using intraoperative TEE. This TEE analysis was performed or reviewed by F.L. or H.J.S. and was the basis for our clinical algorithm using tenting height (ie, end-systolic distance between annular plane and coaptation point, Figure 2A) as surrogate for leaflet tethering to estimate the individual risk of repair failure.

**Clinical Algorithm**

Between 2004 and 2009, patients with annular dilatation and severe leaflet tethering (tenting height ≥10 mm) underwent combination of RING+STRING and represent the study group (RING+STRING, n=30, tenting height 14.1±2.3 mm) for the current investigation. Data were compared with the results of a control group derived retrospectively (RING) of matched patients with tenting height ≥10 mm (n=30, tenting height 13.2±1.5 mm) who underwent standard undersized RING between 2002 and 2004. Patients for this historical control group (RING) were acquired in a retrospective fashion based on review of preoperative echo tapes (reviewed by F.L., M.K., and H.J.S).

Patients requiring LV aneurysmectomy and mitral valve repair were excluded from the current study. Patients with annular dilatation alone or annular dilatation with only minor leaflet tethering (tenting height <10 mm) underwent standard mitral valve repair

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**Figure 1.** Schematic representation of the transventricular suture technique (STRING). A horizontal aortotomy allows exposure of the subvalvular mitral apparatus. A teflon-pledgeted 3-0-polytetrafluoroethylene-suture is anchored in the head of the posterior papillary muscle. The suture is then passed through the fibrosa (midseptal annular saddle horn) underneath the commissure between noncoronary and left coronary aortic cusps under direct vision and exteriorized through the aortic wall. The suture is finally tied under echocardiographical guidance in the loaded beating heart to reposition the displaced posterior papillary muscle toward the fibrosa.

**Figure 2.** A, Assessment of tenting height (ie, end-systolic orthogonal distance between the annular plane and the coaptation point of both mitral leaflets) by intraoperative transesophageal echocardiography. B, Intraoperative transesophageal echocardiography after mitral valve repair and termination of cardiopulmonary bypass with transventricular STRING-suture in situ, resulting in normalized morphology of the mitral valve.
(2002 to 2004: n=44; 2004 to 2009: n=27) and were also excluded from the current study.

**Surgical Technique**

After median sternotomy all patients were placed on cardiopulmonary bypass using aortic and bicaval cannulation. After antegrade blood cardioplegia the mitral valve was exposed via transseptal approach. Standard mitral valve repair included partial RING (Cosgrove-Edwards annuloplasty system, Edwards LifeSciences; SJM Tailor flexible band, St. Jude Medical) in all patients. The annuloplasty band was moderately undersized by 1 to 2 sizes in relation to the intertrigonal distance in all patients and ranged from size 27 to 32. In patients undergoing RING/H11001 annuloplasty band was moderately undersized by 1 to 2 sizes in SJM Tailor flexible band, St. Jude Medical) in all patients. The annuloplasty band was moderately undersized by 1 to 2 sizes in relation to the intertrigonal distance in all patients and ranged from size 27 to 32. In patients undergoing RING+STRING, a horizontal aortotomy was performed after completion of RING. Retraction of the right coronary cusp with a retractor allowed exposure of the anterior mitral leaflet (AML) and both PM. A double-armed Teflon-plugdeted 3-0 polytetrafluoroethylene (PTFE) suture (STRING) was passed through the head of the pPM and then passed from the LV cavity through the aorto-mitral continuity underneath the commissure between the noncoronary and left coronary aortic cusps and exteriorized (Figure 1). In case of a pPM with 2 heads, the suture was anchored in the medial head. During termination of cardiopulmonary bypass, the STRING-suture was tied under TEE guidance in the loaded beating heart. Tension on the suture was titrated under direct visual echocardiographic control in 2D-mode, achieving the most physiological shape of the AML along its entire body and locating the coaptation point as close to the annular plane as possible (Figure 2B). The degree of MR was followed by color Doppler (Figure 3A through 3C). Care was taken to achieve minimal MR and avoid overcorrection with resulting prolapse.

**Echocardiography**

Intraoperative echocardiography in the **RING**+STRING-group was performed or reviewed in all patients by 1 of the 2 investigator (F.L., H.J.S.) using a Siemens Acuson Sequoia 512 (Siemens AG). Intraoperative TEE was used to measure parameters before and after repair. All measurements were obtained via a midesophageal long axis 140 to 150° view. The measured variables included (1) tenting height (ie, end-systolic orthogonal distance between annular plane and coaptation point of both leaflets), (2) tenting area (ie, triangular area formed by the annular plane and the coaptation point of both leaflets at end-systole), and (3) distance between the tip of the pPM and the aorto-mitral continuity. Measurements were obtained during 3 different cardiac cycles and the average value was recorded.

All postoperative echocardiographic studies of both groups were performed by a single investigator (F.L.) using Siemens Sequoia 512 or a GE Vivid 1 (GE Healthcare)—except of patients being referred from distant cardiologists who continued to follow these patients and provided echocardiographic data. Measured variable included severity of MR and end-diastolic and end-systolic LV diameters.

MR grade was quantified as none (0), mild (I), moderate (II), moderate-to-severe (III), and severe (IV) based on regurgitant color jet shape and area in relation to left atrial area in a semiquantitative fashion in all transesophageal and transthoracic studies.21

**Statistical Analysis**

Continuous variables were expressed as mean±SD, ordinal data as median±range. Statistical analysis (SigmaStat 2.0, Jandel Scientific) included comparisons study group versus control group (continuous data: t test, ordinal data: Mann—Whitney U rank test, categorical data: Fisher exact test) or preop. versus postop. data (continuous data: paired t test, ordinal data: Wilcoxon signed rank test). Kaplan–Meier analyses of survival, freedom from reoperation, and freedom from MR>II were also calculated using standard software with Logrank test for curve comparison (Graphpad Prism).

**Results**

Preoperative characteristics of the study patients (n=30) and matched control group patients (n=30) are displayed in Table 1, operative characteristics are displayed in Table 2. In-hospital mortality was similar in both groups. Two patients of the **RING**+STRING group with chronic renal failure and generalized atherosclerosis died from nonocclusive mesenteric ischemia—4 patients of the **RING** control group died from multiple organ failure/sepsis.

**Intraoperative Echocardiographic Data**

IMR was improved in both groups: **RING**+STRING preop.: median III (II: 70%, III–IV: 7%, IV: 23%); postop.: median 0 (no MR: 53%, grade 0-I: 20%, grade I: 23%, I–II: 3%); **RING**: preop. median III (II: 63%, III–IV: 17%, IV: 20%); postop.: median 0 (no MR: 67%, 0-I: 23%, I: 7%, I–II: 3%).
RING+STRING resulted in decreased tenting height (14±2 mm to 6±1 mm*) and area (3.9±0.9 cm² to 1.0±0.2 cm²*). The distance between the pPM and the aorto-mitral continuity was reduced (44±4 mm to 37±3 mm*) in the RING+STRING-group.

Follow-Up Data
Three patients of the RING+STRING group died (lung cancer n=1, sudden cardiac death n=2) within a medium-term follow-up (Figure 4) having stable valve function while alive.

One patient of the RING+STRING group required reoperation 21 months after surgery and underwent successful redo mitral valve repair for structural MR because of A1-prolapse. At the time of reoperation the STRING suture was found intact—the segmental prolapse attributable to chordal elongation was corrected using a 5-0 PTFE-suture as surrogate for a first-order chord. Thus, resulting freedom from reoperation for functional MR was 100% in this group, whereas freedom from reoperation at 2 years postoperatively was 94%. Two patients of the RING control group underwent biological mitral valve replacement for functional MR 5 and 16 months after surgery (freedom from reoperation at 2 years 91%)—1 of these patients died from sepsis 16 days after valve replacement.

Postoperative Echocardiographic Data
MR remained stable during the follow-up in the RING+STRING group—the patient who underwent reoperation was the only individual with MR II. In this group the following echocardiographic results were documented at last follow-up visit (Figure 5): MR median I (no MR: 4%, 0-I: 25%, I: 25%, I–II: 32%, II: 11%, III–IV: 4%). Echocardiographic surveillance in the control-group at last follow-up observed: MR median I (no MR: 4%, 0-I: 11%, I: 38%, I–II: 11%, II: 8%, III–IV: 8%).

Table 1. Preoperative Data

<table>
<thead>
<tr>
<th>Preoperative Data</th>
<th>RING+STRING (n=30)</th>
<th>RING (n=30)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>68±11</td>
<td>70±6</td>
<td>0.51</td>
</tr>
<tr>
<td>Sex, male/female</td>
<td>19/11</td>
<td>20/10</td>
<td>1.00</td>
</tr>
<tr>
<td>BSA, m²</td>
<td>1.9±0.3</td>
<td>1.9±0.2</td>
<td>0.64</td>
</tr>
<tr>
<td>EF, %</td>
<td>37±14</td>
<td>41±15</td>
<td>0.31</td>
</tr>
<tr>
<td>MPAP, mm Hg</td>
<td>34±9</td>
<td>31±13</td>
<td>0.23</td>
</tr>
<tr>
<td>Hypertension</td>
<td>63%</td>
<td>80%</td>
<td>0.25</td>
</tr>
<tr>
<td>DM</td>
<td>37%</td>
<td>53%</td>
<td>0.30</td>
</tr>
<tr>
<td>COPD</td>
<td>53%</td>
<td>57%</td>
<td>1.00</td>
</tr>
<tr>
<td>PVD</td>
<td>33%</td>
<td>37%</td>
<td>1.00</td>
</tr>
<tr>
<td>Stroke</td>
<td>27%</td>
<td>20%</td>
<td>0.73</td>
</tr>
<tr>
<td>CRF</td>
<td>27%</td>
<td>57%</td>
<td>0.30</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td>33%</td>
<td>40%</td>
<td>0.78</td>
</tr>
<tr>
<td>Urgent surgery</td>
<td>20%</td>
<td>27%</td>
<td>0.73</td>
</tr>
</tbody>
</table>

BSA indicates body surface area; NYHA, New York Heart Association; MR, mitral regurgitation; EF, ejection fraction; MPAP, mean pulmonary artery pressure; DM, Diabetes mellitus; COPD, chronic obstructive pulmonary disease; PVD, peripheral vascular disease; CRF, chronic renal failure.

*P<0.05 (study group vs control group).

Table 2. Operative Data

<table>
<thead>
<tr>
<th>Operative Data</th>
<th>RING+STRING (n=30)</th>
<th>RING (n=30)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPB time, min</td>
<td>106±27</td>
<td>103±34</td>
<td>0.45</td>
</tr>
<tr>
<td>X-clamp time, min</td>
<td>68±26</td>
<td>63±19</td>
<td>0.50</td>
</tr>
<tr>
<td>Ring, median (range)</td>
<td>29 (27 to 32)</td>
<td>30 (27 to 32)</td>
<td>0.14</td>
</tr>
<tr>
<td>27 mm</td>
<td>7%</td>
<td>3%</td>
<td>0.14</td>
</tr>
<tr>
<td>28 mm</td>
<td>27%</td>
<td>20%</td>
<td>0.14</td>
</tr>
<tr>
<td>29 mm</td>
<td>30%</td>
<td>3%</td>
<td>0.14</td>
</tr>
<tr>
<td>30 mm</td>
<td>20%</td>
<td>67%</td>
<td>0.14</td>
</tr>
<tr>
<td>31 mm</td>
<td>13%</td>
<td>0%</td>
<td>0.14</td>
</tr>
<tr>
<td>32 mm</td>
<td>3%</td>
<td>7%</td>
<td>0.14</td>
</tr>
<tr>
<td>CABG, grafts</td>
<td>2.9±1.1</td>
<td>2.5±0.7</td>
<td>0.11</td>
</tr>
<tr>
<td>LA- ablation</td>
<td>27%</td>
<td>23%</td>
<td>1.00</td>
</tr>
<tr>
<td>Redo surgery</td>
<td>13%</td>
<td>23%</td>
<td>0.51</td>
</tr>
<tr>
<td>ICU length of stay, h</td>
<td>48 (4 to 864)</td>
<td>45 (12 to 694)</td>
<td>0.89</td>
</tr>
<tr>
<td>Ventilation length, h</td>
<td>23 (2 to 600)</td>
<td>17 (8 to 694)</td>
<td>0.80</td>
</tr>
<tr>
<td>IABP</td>
<td>13%</td>
<td>16%</td>
<td>1.00</td>
</tr>
<tr>
<td>Low-output-syndrome</td>
<td>37%</td>
<td>30%</td>
<td>0.79</td>
</tr>
<tr>
<td>Stroke</td>
<td>0%</td>
<td>0%</td>
<td>1.00</td>
</tr>
<tr>
<td>Operative mortality</td>
<td>7%</td>
<td>13%</td>
<td>0.67</td>
</tr>
</tbody>
</table>

CPB indicates cardiopulmonary bypass; X-clamp, aortic crossclamp; CABG, coronary artery bypass graft; IABP, intraaortic balloon pump; LA, left atrial.

*P<0.05 (study group vs control group).

Figure 4. Survival (Kaplan–Meier with 95% confidence intervals as error bars).

Figure 5. Freedom from mitral regurgitation II (Kaplan–Meier with 95% confidence intervals as error bars).
II–III: 8%, III: 11% III–IV: 8%). Recurrent MR>II was observed as early as 2 to 4 weeks after surgery in 6 of these patients. Systolic gradients were similar in both groups (3.2±0.4 mm Hg versus 3.4±0.6 mm Hg, \(P=0.86\)). Reverse remodeling with decrease of end-diastolic (61.7±7.2 mm to 54.8±9.2 mm, \(P<0.001\)) and end-systolic (48.5±8.5 mm to 42.7±7.8 mm, \(P=0.002\)) LV diameters was observed in the \textit{RING}+\textit{STRING} group. End-diastolic and end-systolic LV diameters persisted in the \textit{RING} control group (Table 3).

<table>
<thead>
<tr>
<th>Echocardiographic Data</th>
<th>\textit{RING}+\textit{STRING} (n=30)</th>
<th>\textit{RING} (n=30)</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preop. LVEDD, mm</td>
<td>61.7±7.2</td>
<td>60.4±7.8</td>
<td>0.34</td>
</tr>
<tr>
<td>Preop. LVEDDI, mm</td>
<td>32.9±4.7</td>
<td>32.8±4.5</td>
<td>0.71</td>
</tr>
<tr>
<td>Preop. LVESD, mm</td>
<td>48.5±8.5</td>
<td>47.8±9.6</td>
<td>0.58</td>
</tr>
<tr>
<td>Preop. LVESDI, mm</td>
<td>26.4±5.9</td>
<td>25.9±5.1</td>
<td>0.54</td>
</tr>
<tr>
<td>Postop. LVEDD, mm</td>
<td>54.8±9.2§</td>
<td>58.9±7.5</td>
<td>0.07</td>
</tr>
<tr>
<td>Postop. LVEDDI, mm</td>
<td>29.1±3.9§</td>
<td>31.6±5.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Postop. LVESD, mm</td>
<td>42.7±7.8§</td>
<td>48.9±5.5</td>
<td>0.07</td>
</tr>
<tr>
<td>Postop. LVESDI, mm</td>
<td>23.1±3.5§</td>
<td>25.7±5.6</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 3. Echocardiographic Data

\(LVEDD\) indicates left ventricular end-diastolic diameter; \(LVEDDI\), left ventricular end-diastolic diameter index; \(LVESD\), left ventricular end-systolic diameter; \(LVESDI\), left ventricular end-systolic diameter index.

\(*P<0.05\) (study group vs control group); \(\dagger P<0.05\) (preop. vs postop.)

Discussion

The results of this study support the following conclusions within a limited follow-up: (1) The combined repair approach using \textit{RING}+\textit{STRING} allows for successful mitral valve repair for IMR in the high-risk subpopulation of patients with severe leaflet tethering, and (2) improvement of MR was associated with LV reverse remodeling once the altered subvalvular geometry was corrected.

Chronic IMR is a common and important complication after myocardial infarction leading to congestive heart failure, and is associated with a poor prognosis.\(^1\) Despite surgical advances, IMR remains a vexing problem in clinical cardiac surgery.\(^{22–25}\) Experimental and clinical studies have clarified the pathogenesis of chronic IMR.\(^{2,18,26}\) Experimental studies from the groups at University of Pennsylvania and Stanford University have identified Carpentier type I leaflet dysfunction attributable to annular dilatation.\(^{27,28}\) Both groups observed dilatation of the muscular ring perimeter as well as dilatation of the intertrigonal distance, which was confirmed in a human necropsy study.\(^{29}\) This observation in conjunction with the successful experimental concept of septal-lateral cinching\(^{30,31}\) supported the hypothesis that undersized RING with a complete device is effective in IMR.\(^{32}\) Best results have been achieved by the use of undersized complete rigid or semirigid rings by the group from Duke and Leiden with reoperation rates as low as 2%.\(^8–10\) Other centers, however, observed residual/recurrent MR in 30%—particularly with the use of partial flexible ring devices.\(^4–7\) The interpretation of these differing results, however, is difficult. The degree of leaflet tethering has not been quantified in many studies, in particular those with apparently positive results of restrictive annuloplasty. Only indirect parameters, such as jet eccentricity, have been described. In the study from Leiden group only 15% of the patients had eccentric regurgitant jets, suggestive of leaflet tethering and indicating that the majority of patients had predominant annular dilatation.\(^10\)

Leaflet tethering as subvalvular component of IMR has been identified as major risk factor for residual/recurrent MR.\(^6,7,11,12,32\) Experimental work from the above mentioned groups from Philadelphia and Stanford confirmed Carpentier type IIb restricted leaflet motion as important mechanism in the pathogenesis of IMR with leaflet tethering attributable to pPM displacement.\(^{18,26}\) Although undersized RING can correct both annular and subvalvular geometry in IMR,\(^2\) RING primarily addresses the annular dilatation. Even undersized RING propagated as annular solution for a ventricular problem fails to eliminate the leaflet tethering as subvalvular component of IMR.\(^6,7,11,33\) Accordingly, Calafiore et al distinguished between good and poor repair candidates based on leaflet tethering characterized by tenting height—if tenting height exceeded 10 mm, valve replacement was performed.\(^34\)

Several techniques have been suggested to address the leaflet tethering. All of these adjunctive techniques, however, represent experimental work—only few techniques have been applied in a larger patient population. The Alfieri technique showed discouraging results in the experience of the Cleveland Clinic.\(^35\) Leaflet extension of the PML has been suggested in the experimental setting\(^36\) and has been successfully used in a case series\(^13\)—however, data of a reasonable patient cohort is lacking. Cutting second-order chordae to eliminate leaflet tethering was initially proposed by Messas et al in the experimental setting.\(^37\) Borger et al from the Toronto group reported lower rate of recurrent MR in patient undergoing adjunctive chordal-cutting (15% versus 37% in the control group).\(^14\) The influence of chordal cutting on LV systolic function is, however, discussed controversially in the literature\(^15,16\)—effects may be even more detrimental in hearts with severely impaired LV function. Finally, new ring design has tried to antagonize the leaflet tethering—the novel Carpentier-McCarthy-Adams IMR ETlogix RING (Edwards LifeSciences) was used with encouraging results.\(^38\) Unfortunately, only 17% of the patients in this multicenter study had significant leaflet tethering with tenting height exceeding 11 mm.

Leaflet tethering or mitral valve tenting as echocardiographic surrogate has been identified as predictor of severity of IMR\(^90\) and is determined by the distance between pPM and the fibrosa.\(^2\) Relocation of the displaced pPM toward the fibrosa may thus be a specific targeted adjunctive repair technique to counteract the altered subvalvular geometry in chronic IMR. Surgical relocation of the displaced pPM has been advocated by Kron et al in a clinical case series.\(^17\) This approach was performed in the arrested heart after completion of RING and included internal pPM relocation using a transventricular suture to anchor the pPM to the mitral annulus aiming posterior to the right fibrous trigone. Based on the geometric distortion associated with chronic IMR reported by Tibayan et al,\(^18\) the repositioning direction was refined in a sheep model of acute IMR.\(^19\) Integrating these 3 studies we developed our new combined concept RING+STRING.\(^20\) In contrast to the Kron technique this concept...
allows precise repositioning of the pPM toward the midseptal fibrous annulus (or saddle horn) in the loaded beating heart. Anchoring the suture in the fibrosa from the atriotomy approach implies the risk of aortic regurgitation if an aortic cusp is inadvertently involved. A horizontal aortotomy facilitates exposure of the subvalvular apparatus and also allows to anchor the suture in the midseptal annulus under direct vision. The final tension on the STRING-suture is determined by tying under direct TEE guidance in the loaded beating heart. 

This technique may aid to eliminate residual MR after RING, but may also prevent recurrent MR in the deleterious continued remodeling process, which leaves the LV as a moving target. The simplicity of the STRING-technique adds minimal to aortic cross clamp time—crucial in severely diseased hearts. In our own limited clinical experience with PML extension we found this technique effective, but have not seen secondary breakdown of artificial chordae attributable to chordal elongation. It appears reasonable to tie under direct TEE guidance in the loaded beating heart. 

As mentioned above Calafiore et al advocated valve replacement if tenting height exceeded 10 mm. We have adopted this arbitrary cut-off point from this publication, however we used this distance to distinguish between standard RING and combined approach using RING + STRING. All patients in the current study had a tenting height exceeding 10 mm—the expected incidence of repair failure in this high-risk subgroup will significantly exceed the reported failure rate of 30%, which has been reported for the overall patient population. Based on the results with the use of the STRING-technique we consider to extend this approach to patients with a tenting height of <10 mm, if we encounter a patient with impaired LV function, history of postero-lateral infarction, and moderate leaflet tethering with tenting height of 7 to 9 mm. 

In the current investigation we tested our hypothesis that correction of Carpentier IIIb leaflet dysfunction is of paramount interest. Thus, we used moderately undersized partial flexible rings despite our suboptimal results in the control group (reoperation rate 7%, MR > II 27%). In doing so we have intentionally limited potential positive effects of ring size and design—supporting the efficacy of our subvalvular strategy. With the adjunctive STRING-technique we achieved not only good freedom from reoperation, but also echocardiographic evidence of improved reverse remodeling. Only one individual of the RING + STRING group exhibited MR > II and required reoperation for A1-prolapse attributable to chordal elongation. It appears reasonable to combine the STRING technique with a rigid ring to optimize annular reduction. Using the combined approach eliminates the need of aggressive annular undersizing with its potential negative hemodynamic effect (ie, patient-prosthesis mismatch in mitral valve repair).

Based on our short- to midterm-term results we can only speculate on the longevity of this new repair approach. We have not seen secondary breakdown of artificial chordae similar as in our experience with chordal replacement for structural MR. The incidence of AML-prolapse in the only patient in this series requiring reoperation was not associated with the STRING technique. During reoperation we found that the prolapse resulted from chordal elongation and was not related to the STRING. The excursion of the AML has not been limited by the STRING suture in the previous experimental setting or in our clinical observations. With our limited follow-up we have not seen indurations or calcifications of leaflet tissue because of possible contact between the AML and the STRING suture. In our current series with the use of moderately undersized partial ring implants we have not observed relevant systolic gradients attributable to the STRING technique—in contrast we speculate that the use of aggressively downsized complete rigid ring implants will be rather associated with higher flow gradients as mentioned above.

Long-term follow-up, however, has to prove the clinical role of this new repair option for patients with IMR.

**Study Limitations**

The major drawback of the current investigation is that the study was designed as a prospective nonrandomized study. A controlled prospective randomized study involving different treatment arms (CABG alone, CABG + RING, CABG + RING + STRING) with different subgroups (complete versus partial RING, rigid versus flexible, aggressive versus moderate downsizing) would ultimately have highest scientific impact. Such an ideal study is difficult to realize as single center experience in daily clinical practice. Thus a historical control group was derived from 30 matched patients in a retrospective fashion based on the key parameter tenting height in preoperative TEE in both groups. Moreover, both groups matched in all aspects of preoperative and perioperative data.

A potential limitation of the echocardiographic surveillance is the use of semiquantitative grading of MR severity instead of the use of regurgitant volume or effective regurgitant orifice. However, IMR is frequently associated with complex jets—acquisition of the latter parameters, however, is limited with this jet morphology. Moreover, end-diastolic and end-systolic diameters were used as the only surrogates for reverse remodeling. These simple crude echocardiographic parameters, however, allow the least error for investigator-related bias—important for the few distant patients being followed by their local cardiologists. More precise studies using MRI would have acquired more precise information about LV reverse remodeling.

**Sources of Funding**

This work was supported by departmental funding.

**Disclosures**

None.

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Circulation. 2009;120:S85-S91
doi: 10.1161/CIRCULATIONAHA.108.840173
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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