Effects of Paracommissural Septal-Lateral Annular Cinching on Acute Ischemic Mitral Regurgitation

Tomasz A. Timek, MD; David T. Lai, FRACS; David Liang, MD, PhD; Frederick Tibayan, MD; Frank Langer, MD; Filiberto Rodriguez, MD; George T. Daughters, MS; Neil B. Ingels, Jr, PhD; D. Craig Miller, MD

Background—Previous experimental studies demonstrated that central septal-lateral (SL) annular cinching (SLAC) abolishes acute ischemic mitral regurgitation (IMR), but whether localized cinching near the anterior (ACOM) or posterior (PCOM) commissure is equally effective is unknown.

Methods—Six adult sheep underwent implantation of 9 radiopaque markers on the left ventricle, 8 around the mitral annulus (MA) and 1 on each papillary muscle (PM) tip. Transannular SL sutures were placed at the valve center (CENT) and near ACOM and PCOM and externalized. Acute IMR was induced by proximal circumflex coronary snare occlusion. Biplane videofluoroscopy and transesophageal echocardiography were performed before and continuously during 3 episodes of myocardial ischemia including 20 seconds of SLAC at each different location. End-systolic MA SL dimension at each suture location and distances between the anterior and posterior PM tips and mid-septal annulus (“saddle horn”) were calculated from the 3-dimensional (3D) marker coordinates.

Results—SLAC interventions in all 3 locations reduced the degree of IMR, but cinching at the center, SLACCENT, had a significantly greater effect on reducing the magnitude of IMR than SLACPCOM or SLACACOM (mean grade of IMR reduction = 1.0 ± 0.5, 1.8 ± 0.5, and 0.9 ± 0.2 for SLACACOM, SLACCENT, and SLACPCOM, respectively; P = 0.044). Although ACOM and PCOM cinching reduced SLCENT somewhat, only SLACCENT simultaneously reduced both SLACOM and SLPCOM and also repositioned both PM tips closer to the annular saddle horn.

Conclusions—SLAC in all 3 positions reduced acute IMR, but central SLAC cinching was most effective, reduced all mitral annular SL dimensions, and relocated both PM tips closer to the mid-septal annulus. Central SLAC is most capable of correcting the annular and subvalvular perturbations accompanying acute left ventricular ischemia that lead to IMR. (Circulation. 2004;110[Suppl II]:II-79–II-84.)

Key Words: ischemia ■ ischemic mitral regurgitation ■ mitral valve ■ surgery

Surgical treatment of ischemic mitral regurgitation (IMR) continues to be hampered by suboptimal clinical results and excessive long-term mortality.1–4 Mitral valve repair is preferred to valve replacement for most causes of mitral regurgitation5,6 but remains challenging for patients with IMR.7 Currently, small ring annuloplasty represents the standard mitral repair technique for IMR, but as the complex pathophysiology of valvular–ventricular interactions in chronic IMR becomes better-elucidated,8,9 newer experimental reparative techniques are being proposed to address this challenging disease. We previously described an experimental technique of septal-lateral annular cinching (SLAC) with a central transannular suture to treat acute IMR.10 This simple form of valvuloplasty corrected both annular and subvalvular geometric perturbations associated with acute ovine IMR while maintaining near-normal mitral leaflet motion.10 Similar results were recently presented with the transventricular Coapsys device based on subannular SL reduction.12 Thus, it appears that annular interventions also affect left ventricular (LV) geometry and may address the “ventricular disease” component of ischemic mitral regurgitation. Although central SLAC is effective in abolishing acute IMR, whether more localized SLAC near the anterior (ACOM) or posterior (PCOM) commissure would be equally efficacious is un-
known. To investigate this question, we placed 3 transannular sutures and implanted miniature radiopaque markers on the mitral apparatus in healthy adult sheep to study the effect of paracommissural annular cinching on IMR and valvular and subvalvular geometry during acute LV myocardial ischemia.

**Methods**

**Surgical Preparation**

Six adult sheep were used, and the detailed operative details for marker implantation has been described previously. The markers were implanted on the left ventricle, around the mitral annulus, and on each papillary muscle tip. The annular marker array is shown in Figure 1. Subsequently, a single 3-0 polypropylene suture was anchored with a pledget at the mid-septal annulus (annular “saddle horn”) and externalized through the mid-lateral annulus to a tourniquet on the epicardial surface. Two other similar sutures (without pledges) were anchored at the right and left fibrous trigones and externalized through their corresponding opposite portions of the lateral annulus. Sutures were externalized to epicardial tourniquets. PML indicates posterior mitral leaflet; AML, anterior mitral leaflet; AV, aortic valve. Arrow points to the direction of annular cinching.

**Data Acquisition and Analysis**

Data acquisition, digital transformation, and 3-dimensional (3D) reconstruction were performed as previously described. Two to 3 consecutive steady-state beats during IMR and during each SL annular cinching at valve center or near the anterior or the posterior commissure (designated as SLACCENT, SLACACOM, and SLACPCOM, respectively) were recorded for each animal. End-systole was defined as the frame containing the peak rate of decrease of LV pressure (-dP/dt) and end-diastole as the videofluoroscopic frame containing the peak of the ECG R-wave. Instantaneous LV volume was computed from the epicardial LV markers using a space-filling multiple tetrahedral volume method. The amount of mitral regurgitation (MR) was graded subjectively by an experienced cardiologist (D.L.) according to the extent and width of the regurgitant jet and categorized as none (0), mild (+1), moderate (+2), moderate to severe (+3), or severe (+4).

**Mitral Annular Dynamics**

Mitral annular area was computed from the 3D coordinates of the 8 markers sutured to the mitral annulus by defining an annular centroid, then dividing the annulus into 8 triangular areas that were summed to yield total annular area. Mitral SL annular diameters were calculated at the three SLAC suture locations as the distance in 3D space between the corresponding marker pairs across the septal and lateral annulus. To assess the effect of annular cinching interventions on subvalvular geometry, the distance from the anterior and posterior papillary muscle tips to the mid-septal annular “saddle horn” was calculated before and after each SLAC intervention. The 3D shape of the mitral annulus was represented by calculating mitral annular height defined as the orthogonal distance of the annular saddle horn from the least squares plane fitted to the lateral annular markers.

**Statistical Analysis**

All data are reported as mean ± 1 SD. Hemodynamic and marker-derived data from consecutive steady-state beats from each heart were time-aligned at end-diastole. Marker data were calculated over 20 frames before and after end-diastole, thus allowing evaluation over a time period of 650 ms. The mean and SD for each variable at each sampling instant were computed for each condition. Measured variables before and after cinching interventions were compared using Student's t test for dependent observations.
TABLE 1. Hemodynamics

<table>
<thead>
<tr>
<th></th>
<th>ACOM</th>
<th>CENT</th>
<th>PCOM</th>
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<tbody>
<tr>
<td></td>
<td>Before Cinch</td>
<td>Cinch</td>
<td>Before Cinch</td>
</tr>
<tr>
<td>DP/dt (mm Hg/s)</td>
<td>1450±430 (950–2001)</td>
<td>1314±355* (911–1689)</td>
<td>1260±23936 (977–1582)</td>
</tr>
<tr>
<td>LVP (mm Hg)</td>
<td>88±17 (72–117)</td>
<td>82±15* (68–106)</td>
<td>84±7 (74–92)</td>
</tr>
<tr>
<td>EDV (mL)</td>
<td>191±38 (139–242)</td>
<td>189±35* (138–241)</td>
<td>185±33 (140–232)</td>
</tr>
<tr>
<td>EDP (mm Hg)</td>
<td>17±7 (8–25)</td>
<td>16±7* (6–26)</td>
<td>16±7 (8–28)</td>
</tr>
<tr>
<td>MR (0–4)</td>
<td>1.8±0.3 (0.8–4*)</td>
<td>0.8±0.4*</td>
<td>2.3±0.5 (0.6–4*)</td>
</tr>
</tbody>
</table>

ACOM indicates septal-lateral suture near anterior mitral commissure; CENT, septal-lateral suture at mid-septal annulus; PCOM, septal-lateral suture near posterior commissure; HR, heart rate; dP/dt, maximum LV +dP/dt; LVP, peak LV pressure; EDV, end-diastolic volume; EDP, end-diastolic pressure; MR, mitral regurgitation.

Range of values given in parentheses.

*P<0.05 vs before cinching by t test for dependent observations.

Results

Hemodynamics

Average sheep weight was 65±5 kg. Mean cardiopulmonary bypass time was 79±8 minutes, and average aortic cross-clamp time was 58±6 minutes. Table 1 summarizes the hemodynamic variables during acute LV ischemia before and during each of the 3 SLAC interventions. There was no difference in the hemodynamic parameters between the 3 SLAC steps before or during cinching suggesting an equivalent ischemic insult for all interventions. LV dP/dt and peak LV pressure decreased after cinching with SLACACOM, but otherwise all hemodynamic parameters for this and the other 2 interventions did not change during cinching. Before induction of acute posterolateral ischemia, 3 animals had no MR at baseline, 1 trace insufficiency, and 2 mild MR for a mean MR grade of 0.4 ± 0.5. All SL anular reducing maneuvers decreased the degree of IMR, but cinching at the valve center had a significantly greater effect on reducing the magnitude of IMR than SLACPCOM or SLACACOM (mean degree of IMR reduction of 1.0±0.5, 0.9±0.2, and 1.8±0.5 for SLACACOM, SLACPCOM, and SLACCENT, respectively; P=0.044).

Annular and Subvalvular Geometry

End-systolic measurements of mitral annular area, annular height, and the 3 annular SL diameters before and after each cinching intervention are shown in Table 2. The distance between both papillary muscle tips to the annular “saddle horn” is also shown for the 3 SLAC steps. Mitral annular area was reduced significantly by each SLAC maneuver (mean decrease in mitral annular area of 0.9±0.3 cm², 1.0±0.5 cm², and 0.6±0.3 cm² for SLACACOM, SLACCENT, and SLACPCOM, respectively). Mitral annular saddle horn height did not change with any of the cinching interventions; thus, annular flattening was not observed during each suture cinching. Annular SL diameter was reduced at valve center and near both commissures with SLACACOM and SLACCENT, but with SLACPCOM only SLPCOM and SLPCENT were affected. At the subvalvular level, only central SLAC cinching reduced the distance between both papillary muscle tips and the annular

TABLE 2. Annular and Subvalvular Geometry at End-Systole During Acute Ischemia

<table>
<thead>
<tr>
<th></th>
<th>ACOM</th>
<th>CENT</th>
<th>PCOM</th>
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<tbody>
<tr>
<td></td>
<td>Before Cinch</td>
<td>Cinch</td>
<td>Before Cinch</td>
</tr>
<tr>
<td>SLACOM</td>
<td>1.70±0.24 (1.19±0.18*)</td>
<td>1.80±0.20 (1.56±0.23*)</td>
<td>1.83±0.25 (1.71±0.19)</td>
</tr>
<tr>
<td>SLCENT</td>
<td>2.94±0.25 (2.76±0.28*)</td>
<td>2.83±0.21 (2.30±0.38*)</td>
<td>2.93±0.15 (2.68±0.16*)</td>
</tr>
<tr>
<td>SLPCOM</td>
<td>2.68±0.21 (2.63±0.20*)</td>
<td>2.65±0.21 (2.51±0.18*)</td>
<td>2.62±0.18 (2.36±0.17*)</td>
</tr>
<tr>
<td>APM saddle horn</td>
<td>4.95±0.32 (4.90±0.30*)</td>
<td>4.92±0.32 (4.82±0.30*)</td>
<td>4.94±0.32 (4.97±0.35)</td>
</tr>
<tr>
<td>PPM saddle horn</td>
<td>5.22±0.34 (5.20±0.35)</td>
<td>5.18±0.36 (5.07±0.32*)</td>
<td>5.22±0.32 (5.25±0.35)</td>
</tr>
<tr>
<td>MAH (cm²)</td>
<td>0.59±0.19 (0.72±0.47)</td>
<td>0.61±0.25 (0.57±0.22)</td>
<td>0.61±0.19 (0.60±0.20)</td>
</tr>
<tr>
<td>MAA (cm²)</td>
<td>8.51±0.95 (7.63±0.89*)</td>
<td>8.62±0.87 (7.61±1.14*)</td>
<td>8.66±0.71 (8.10±0.73*)</td>
</tr>
</tbody>
</table>

MAA indicates mitral annular area; MAH, mitral annular height; SL, septal-lateral annular diameter; APM, anterior papillary muscle tip; PPM, posterior papillary muscle tip; saddle horn, center of septal annulus.

*P<0.05 vs. before cinching by t test for dependent observations.
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both SL ACOM and SL PCOM along with substantial decrease in SL CENT; and SLAC PCOM reduced SL CENT as well as SL PCOM, but level, only SLAC CENT had a significant effect on decreasing (AV), right

Figure 4. Schematic diagram of the mitral annulus, aortic valve (AV), right fibrous trigone (RFT), left fibrous trigone (LFT), and anterior (APM) and posterior (PPM) papillary muscles representing the changes in measured 3D distances (dashed lines) after septal–lateral annular cinching of the anterior commissure (ACOM) transannular suture. Only significant changes (P < 0.05 versus precinching) in measured distances are shown. Arrow shows the direction of annular cinching.

“saddle horn.” To better assess the magnitude of geometric alteration induced in the valvular apparatus with each SLAC step, the difference in the measured annular and subvalvular 3D distances before and after each cinching step was calculated and are presented in Figures 3 to 5. At the annular level, SLAC_ACOM reduced SL_ACOM and SL_CENT and, to a lesser degree, SL_PCOM; SLAC_CENT had an almost equal effect on reduction of both SL_ACOM and SL_PCOM along with substantial decrease in SL_CENT, and SLAC_PCOM reduced SL_CENT as well as SL_PCOM, but had no effect on SL_ACOM. The reduction of SL_CENT and SL_ACOM was about the same (∼5 mm) with the respective SLAC step, whereas SL_PCOM was reduced by 2.6 mm. At the subvalvular level, only SLAC_CENT had a significant effect on decreasing the distance between both papillary muscle tips and the mid-septal annulus; this effect was approximately the same for both papillary muscles.

Discussion

Ischemic mitral regurgitation continues to challenge surgeons as optimal surgical corrective methods still remains to be defined. Although annular reduction, usually with ring annuloplasty, has been central to the surgical treatment of patients with IMR, the failure rate is considerable,18 and some question the use of an annular prosthesis to treat a “ventricular disease.” Annular dilatation during acute ischemia is mainly in the SL direction,19 and isolated reduction of the central annular SL diameter abolishes IMR in acute as well as chronic animal models.10,12 The current study was designed to evaluate whether annular SL diameter reduction near the commissures would be as effective as central SLAC. We found that all 3 annular reducing interventions were effective in decreasing the degree of IMR, yet central annular SL reduction had the greatest effect on the magnitude of IMR reduction and was the only intervention that repositioned both papillary muscle tips closer to the mid-septal annulus.

Chronic mitral regurgitation in humans9 and experimental animals8 is associated with significant mitral annular dilation and alterations is subvalvular geometry as manifested by displacement of the papillary muscle tips relative to the mitral annulus. Thus, it follows that surgical repair of IMR should correct these perturbations at both the annular and the ventricular levels. Some investigators propose that annular reduction with an undersized annuloplasty ring not only corrects the dilated mitral orifice but also leads to ventricular remodeling and correction of functional mitral regurgitation (FMR) in end-stage heart failure patients.20 Experimental studies suggest a similar effect because ring annuloplasty has been shown to prevent leaflet tethering, arising from altered papillary muscle position, during acute IMR.21 A previous report from our laboratory demonstrated that isolated central annular SL reduction not only eliminated IMR but also affected the position of both papillary muscles relative to the mid-septal annulus.11 These studies provided support that a simple annular surgical intervention can simultaneously alter subvalvular geometry. Isolated subvalvular procedures such as ventricular free wall plication,22 external restraint,23 and second-order chordal cutting24 have also been successful in correcting IMR. In our experiment, annular SL cinching near
the anterior commissure had only a modest effect on anterior papillary muscle tip position, whereas annular reduction near the posterior commissure did not alter position of either papillary muscle tip. These data suggest that reduction of ischemic mitral regurgitation is feasible without altering subvalvular geometry, yet these interventions reduced IMR by only \( \approx 1 \) grade. Central annular cinching resulted in significantly greater control of acute mitral insufficiency than did paracommissural cinching and also was associated with papillary muscle tip repositioning. Thus, it appears that optimal treatment of acute IMR requires correction of abnormal geometry of both the annulus as well as the subvalvular apparatus. In vitro studies corroborate this supposition as mitral annular dilation can lead to MR, but MR is greatly increased by concurrent papillary muscle displacement.\(^{25}\) Thus, by correcting annular dilation alone, IMR can be reduced but not eliminated if papillary muscle displacement is also present. Our data corroborate this hypothesis as paracommissural annular reductions had a lesser influence on reducing the magnitude of IMR.

The annulus is vital component of the mitral apparatus, although it is a poorly defined structure described as a discontinuous fibrous ring\(^{26,27}\) with a heterogeneous mixture of atrial and ventricular myocardial fibers. Observations from the current study suggest that the annulus is functionally a coupled unit as site-specific annular interventions resulted in altered geometry in adjacent and distant segments of the annulus. Central annular SL cinching resulted in not only significant reduction of \( S_{\text{CENT}} \) but also the SL diameters near each commissure. However, each paracommissural SLAC also reduced central mitral SL diameter. All cinching steps resulted in significant decrease in mitral annular area. Therefore, the effects of each SLAC intervention were not strictly localized even at the annular level, underscoring the dynamic interplay between the components of the mitral valve apparatus. None of the SLAC interventions, however, affected mitral annular height. This probably is favorable because the natural 3D shape of the mitral annulus is important for proper leaflet stress distribution.\(^{28}\) In a recently reported clinical series of patients with ischemic mitral regurgitation,\(^4\) 58% were found to have a central regurgitant jet with 7%, 20%, and 15% having anterior, posterior, or complex jets, respectively. A majority of these patients were treated with annuloplasty only. A SLAC-type repair may be well-suited to address this heterogeneity with a single transannular suture or a combination of sutures by providing a custom-tailored paracommissural repair targeted at the origin of the jet in addition to central SL annular reduction to increase central leaflet coaptation without altering leaflet motion\(^{10,29}\) and correct subvalvular perturbations. The theoretical advantage of this approach remains speculative at this time, and the efficacy of a combination of SLAC interventions remains to be studied. It is the heterogeneity of the mitral annulus that may also account for greater MR reduction with central suture cinching. Previous studies have shown that myocardial insults whether global\(^{10}\) or localized\(^{31}\) have a differential effect on segmental dynamics of the mitral annulus. Thus, sutures spanning across different segments of the annulus should be expected to have a varying effect on abolishing ischemic mitral insufficiency. In addition, cinching the annulus at 1 location has a differential effect on adjacent annular segments further underlying the heterogeneous structure and functional dynamics of the mitral annulus. Further study into the detailed functional anatomy of this yet poorly understood structure should bear fruit in more rational approaches for surgical correction of ischemic mitral regurgitation.

The complex challenges posed by surgical correction of IMR continue to be a major clinical problem. This experimental study provides further insight into the mechanisms and potential treatment of IMR. These data demonstrate that the mitral apparatus is a tightly coupled dynamic system, and local anular interventions may affect geometry of the entire annulus and the subvalvular apparatus. Although paracommissural SLAC was effective in reducing the degree of acute IMR, it did not equal the effectiveness obtained with central SLAC, associated with restoration of subvalvular geometry. These findings reinforce the notion that optimal surgical repair of IMR should strive to correct valvular and subvalvular geometric perturbations.

**Study Limitations**

It is important to acknowledge that acute ovine IMR does not reflect the clinical entity in which chronic LV remodeling and chamber dilatation may have predominant effects on the pathogenesis of IMR, but the geometric perturbations observed in both acute\(^{20}\) and chronic\(^{2}\) ovine IMR are qualitatively similar although their magnitudes differ. The magnitude of \( S_{\text{PCOM}} \) reduction with SLAC\(_{\text{POM}} \) was less than for the other 2 SL diameters with the respective SLAC steps. Thus, it is feasible that greater cinching of \( S_{\text{POM}} \) (ie, closer to 0.5 cm) might have been more effective in reducing IMR; however, the regurgitant jet in acute ovine IMR is mainly central,\(^{30}\) and the efficacy of either paracommissural cinching intervention would most likely be related to the associated reduction of the central SL mitral annular diameter. Mitral regurgitation before central SLAC was greater than for the other 2 interventions possibly because of instability of the animal preparation or ischemic preconditioning. Between each ischemic intervention, however, the animals were allowed to rest for 5 to 10 minutes to return to pre-ischemic hemodynamic equilibrium. Importantly, with the induction of acute posterolateral ischemia, the “baseline” ischemic pre-SLAC hemodynamics did not differ between the groups suggesting an equivalent ischemic insult. Whether the difference in pre-intervention MR grade was caused by ischemic preconditioning or occult changes in baseline nonischemic cardiac function cannot be determined. It is also possible that the higher degree of pre-intervention MR with central SLAC was caused by a measurement error, but this is unlikely. Mitral regurgitation was assessed by an experienced echocardiographer using transesophageal echocardiography. For each intervention in every animal, the valve was scanned from commissure to commissure to assess MR grade based on visualizing the entire valve. The myocardial marker method requires suturing small metal markers to intracardiac structures, but echocardiographic studies suggest that the markers do not interfere with mitral annular or leaflet motion because they are very small (aggregate mass=20±6 mg). The MR
was graded qualitatively using standard clinical criteria rather than as quantitative regurgitant volume, but clinical criteria seem particularly appropriate for the purposes of the present study.

Acknowledgments

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References


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