Paneth Suture Annuloplasty Abolishes Acute Ischemic Mitral Regurgitation but Preserves Annular and Leaflet Dynamics

Frederick A. Tibayan, MD; Filiberto Rodriguez, MD; David Liang, MD, PhD; George T. Daughters, MS; Neil B. Ingels, Jr, PhD; and D. Craig Miller, MD

Background—Ring annuloplasty, the standard treatment for ischemic mitral regurgitation (IMR), abolishes normal annular dynamics and freezes the posterior leaflet. We examined the impact of Paneth suture annuloplasty during acute IMR on motion of the mitral annulus and leaflets in an ovine model.

Methods and Results—Eight sheep had radiopaque markers placed on the left ventricle, anterior mitral leaflet, posterior mitral leaflet, and mitral annulus. A Paneth suture annuloplasty that could be reversibly tightened was anchored to each fibrous trigone and externalized through the mid-lateral mitral annulus. Acute IMR was induced by proximal circumflex artery occlusion. Transesophageal echocardiography assessed the degree of IMR, and biplane cinefluoroscopy measured 3-dimensional marker coordinates before and during circumflex ischemia, and tightening of the Paneth suture. Paneth suture annuloplasty eliminated acute IMR, and reduced septal-lateral and commissure-commissure mitral annular dimensions. Tightening of the annuloplasty sutures, even beyond the degree necessary to eliminate mitral regurgitation (MR), did not reduce septal-lateral or commissure-commissure annular shortening, shortening of the muscular annular perimeter, annular flexion, or angular excursion of the anterior or posterior leaflets relative to ischemic conditions.

Conclusions—In contrast to ring annuloplasty, annular reduction sufficient to restore mitral competence during acute IMR can be achieved with a Paneth suture annuloplasty while simultaneously maintaining normal annular and leaflet dynamic motion. These findings should prompt additional investigation and design of repair methods that preserve the mobility of the mitral apparatus. (Circulation. 2003;108[suppl II]:II-128–II-133.)

Key Words: mitral repair • ischemic mitral regurgitation • acute myocardial ischemia

Ring annuloplasty is the preferred repair method for IMR, but both semirigid1,2 and flexible1,3,4 rings abolish normal annular dynamics and freeze the posterior mitral leaflet in the semiopen position.1,3 Procedures that reduce annular size while preserving physiological annular and leaflet motion may be advantageous because: (1) diastolic increase in annular area may aid LV filling;5 (2) finite element models predict that annular flexibility is associated with reduced leaflet and chordal stress;6 and (3) annular reduction with preserved annular dynamics would maintain more normal timing of leaflet opening and closing.2 Paneth suture annuloplasty might be a means of reducing the size of the annulus while maintaining physiological annular and leaflet motion,4 but its effects on 3-dimensional mitral dynamics are unknown. We tested the hypothesis that Paneth suture annuloplasty would eliminate acute IMR while preserving physiological mitral annular and leaflet motion.

Methods

Surgical Preparation

Eight adult sheep were used, and the operative techniques for marker implantation have been described previously in detail.1 Before marker implantation, a double loop of 2 to 0 Prolene was placed around the left circumflex coronary artery proximal to the first obtuse marginal branch for induction of posterolateral myocardial ischemia causing acute IMR. On cardiopulmonary bypass, radiopaque markers were implanted on the left ventricle, around the mitral annulus, and on the central edge of each leaflet as shown in Figure 1. A modified Paneth-Burr suture annuloplasty8 was performed as follows. A double-armed, pledged 2 to 0 polypropylene suture was anchored at the right fibrous trigone, sutured around the posterior annulus, and externalized through the midlateral annulus to an epicardial tourniquet as shown in Figure 2. A similar suture was placed from the left fibrous trigone and externalized through the midlateral annulus on a separate tourniquet. After weaning from cardiopulmonary bypass, a micromanometer pressure transducer (PA4.5-X6; Konigsberg Instruments, Inc.) was placed in the left ventricular (LV) chamber through the apex. The animal was then transferred immediately to the experimental catheterization laboratory and studied intubated, open-chest, and anesthetized with inhalational isoflurane (1.5–2.0%).

Data acquisition, digital transformation, and reconstruction of 3-dimensional marker coordinates were performed as described previously.9 For each animal, 3 consecutive steady-state beats during control conditions, circumflex ischemia, and ischemia after each of 2 successive 5–7-mm pulls on the Paneth sutures were designated as Baseline, Ischemia, ASP-1, and ASP-2, respectively (ASP=“Annuloplasty Suture Pull” 1 and 2). End-systole was de-
Two double-armed 2 to 0 polypropylene sutures were anchored at each fibrous trigone (LFT=left fibrous trigone; RFT=right fibrous trigone) extended around the annulus, and exteriorized through the midlateral annulus to adjustable tourniquets.

Mitral Leaflet Excursion
To assess leaflet motion throughout the cardiac cycle, anterior mitral leaflet angle, \( \theta_{AML} \), was calculated as the angle in 3-dimensional space between the annular septal-lateral diameter and the chord between the midseptal annular marker and anterior leaflet edge marker; similarly, the posterior mitral leaflet edge angle, \( \theta_{PML} \), was defined as the angle formed by the septal-lateral diameter and the chord between the midlateral annulus and the posterior leaflet edge marker. Leaflet excursion was calculated as the range (maximum to minimum angle) of the respective leaflet angles throughout the cardiac cycle.

Statistical Analysis
All of the data are reported as mean ± 1 SD, unless otherwise stated. Hemodynamic and geometrical data were compared with determine changes after induction of ischemia and after tightening of the suture annuloplasty (Baseline versus Ischemia and Ischemia versus ASP-1 and ASP-2) using repeated measures ANOVA with Dunnett’s test for multiple comparisons when ANOVA yielded a significant F value (\( P<0.05 \)).

Results
Table 1 summarizes group mean hemodynamic data at Baseline, Ischemia, and during ischemia with cinching of the suture annuloplasty (ASP-1 and ASP-2). During ischemia, LV end-diastolic volume, IMR, and LV end-diastolic pressure increased significantly, whereas LV dP/dt decreased. The first stage of annuloplasty tightening (ASP-1) returned IMR to baseline levels, but did not affect heart rate, dP/dt, end-diastolic volume, or end-diastolic pressure. The second pull on the Paneth sutures did not additionally affect the measured hemodynamic variables.

Table 2, and Figures 3 and 4 summarize annular dynamics during baseline conditions, during ischemia, and during ischemia with suture annuloplasty cinching. As expected, during ischemia both maximum and minimum mitral annular septal-lateral and commissure-commissure diameters increased, and septal-lateral and commissure-commissure annular shortening decreased. Tightening of the suture annulo-
plasty sufficient to eliminate acute IMR (ASP-1) reduced septal-lateral and commissure-commissure annular diameters, but did not reduce annular diameter shortening relative to the ischemic state. Additional tightening of the annuloplasty suture (ASP-2) still did not decrease annular shortening.

During ischemia, the length of the muscular annulus increased, and shortening of this muscular perimeter decreased. Tightening the suture annuloplasty (ASP-1 and ASP-2) reduced the length of the muscular annulus, without any additional effect on its relative shortening compared with ischemia. Annular height and annular flexion fell with ischemia. Additional tightening of the annuloplasty annuloplasty had no additional effect on annular flexion relative to ischemic conditions.

Table 3 and Figure 5 summarize the mitral leaflet maximum and minimum angles and angular leaflet excursion at Baseline, Ischemia, ASP-1, and ASP-2. Ischemia had no effect on anterior leaflet excursion, and tightening the suture annuloplasty did not change anterior leaflet mobility. During ischemia, posterior leaflet angular excursion also did not change. Annular reduction with suture annuloplasty at 2 successive stages, even beyond that necessary to restore mitral competence (ASP-2), also did not affect posterior leaflet excursion.

### Discussion

Preservation of the normal physiology and mobility of the mitral valve apparatus has long been a goal of mitral valve reparative surgery. Chordal-sparing mitral valve replacement,11 Carpentier’s mitral repair techniques,12 flexible ring annuloplasty,13 suture,8 and pericardial strip14 annuloplasty have all attempted to restore or maintain normal mitral valve function. Whereas ring annuloplasty is the most commonly used reparative procedure in treating patients with IMR, rings of all types, whether rigid1,2,4 or flexible1,4,15, partial1,6 or complete1,15, abolish normal annular dynamics and freeze the posterior leaflet in the semiopen position. Methods of annular reduction without a ring have been proposed to maintain more physiological annular and leaflet motion,2,14,17,18 but the effects of such methods on annular and leaflet dynamics are unknown. The key findings of this study are: (1) annular reduction with a Paneth suture annuloplasty eliminated acute IMR and maintained annular dynamic shortening and flexion; and (2) tightening the Paneth suture annuloplasty did not reduce either anterior or posterior mitral leaflet excursion. Paneth suture annuloplasty abolished acute IMR in this study by decreasing septal-lateral and commissure-commissure annular diameters. Septal-lateral annular dilation has been shown to be the principal cause of leaflet malcoap-

### TABLE 1. Hemodynamic Variables

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Ischemia</th>
<th>ASP-1</th>
<th>ASP-2</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR (0–4+)</td>
<td>0.3±0.3*</td>
<td>2.1±0.4</td>
<td>0.6±0.5*</td>
<td>0.5±0.4*</td>
<td>35.5</td>
</tr>
<tr>
<td>Heart rate (min⁻¹)</td>
<td>106±21</td>
<td>96±31</td>
<td>99±21</td>
<td>99±21</td>
<td>1.1</td>
</tr>
<tr>
<td>LV dP/dt (mm Hg/s)</td>
<td>2,666±351*</td>
<td>1,813±425</td>
<td>1,648±301</td>
<td>1,636±319</td>
<td>28.5</td>
</tr>
<tr>
<td>EDV (ml)</td>
<td>132±46*</td>
<td>158±50</td>
<td>151±53</td>
<td>151±54</td>
<td>14.1</td>
</tr>
<tr>
<td>ESV (ml)</td>
<td>101±33*</td>
<td>127±39</td>
<td>126±44</td>
<td>126±44</td>
<td>18.4</td>
</tr>
<tr>
<td>LVEDP (mm Hg)</td>
<td>14±4*</td>
<td>21±4</td>
<td>20±4</td>
<td>20±4</td>
<td>15.1</td>
</tr>
</tbody>
</table>

*=P<0.05 vs. Ischemia by repeated measures ANOVA and Dunnett’s test.

MR = mitral regurgitation; dP/dt = maximum rate of LV pressure versus time; EDV = end-diastolic volume; ESV = end-systolic volume; F = F value from repeated measures ANOVA.

### TABLE 2. Annular Dynamics

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Ischemia</th>
<th>ASP-1</th>
<th>ASP-2</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-L max (cm)</td>
<td>2.6±0.3*</td>
<td>3.0±0.4</td>
<td>2.6±0.7*</td>
<td>2.5±0.7*</td>
<td>16.7</td>
</tr>
<tr>
<td>S-L min (cm)</td>
<td>2.2±0.2*</td>
<td>2.6±0.4</td>
<td>2.4±0.6*</td>
<td>2.3±0.6*</td>
<td>11.5</td>
</tr>
<tr>
<td>S-L shortening (%)</td>
<td>15±4*</td>
<td>10±4</td>
<td>8±4</td>
<td>8±3</td>
<td>21.1</td>
</tr>
<tr>
<td>C-C max (cm)</td>
<td>3.3±0.4*</td>
<td>3.6±0.3</td>
<td>3.3±0.6*</td>
<td>3.2±0.7*</td>
<td>10.6</td>
</tr>
<tr>
<td>C-C min (cm)</td>
<td>3.0±0.4*</td>
<td>3.4±0.3</td>
<td>3.2±0.6*</td>
<td>3.1±0.7*</td>
<td>13.8</td>
</tr>
<tr>
<td>C-C shortening (%)</td>
<td>8±3*</td>
<td>5±1</td>
<td>5±3</td>
<td>6±3</td>
<td>3.9</td>
</tr>
<tr>
<td>Muscular annulus max (cm)</td>
<td>6.6±0.9*</td>
<td>7.1±0.7</td>
<td>6.4±1.1*</td>
<td>6.1±1.1*</td>
<td>8.7</td>
</tr>
<tr>
<td>Muscular annulus min (cm)</td>
<td>6.0±0.9*</td>
<td>6.7±0.6</td>
<td>6.1±1.0*</td>
<td>5.8±1.0*</td>
<td>8.2</td>
</tr>
<tr>
<td>Muscular annulus shortening (%)</td>
<td>10±4*</td>
<td>5±2</td>
<td>5±2</td>
<td>5±2</td>
<td>8.7</td>
</tr>
<tr>
<td>Annular height max (cm)</td>
<td>0.8±2*</td>
<td>0.6±0.2</td>
<td>0.6±0.3</td>
<td>0.6±0.3</td>
<td>6.9</td>
</tr>
<tr>
<td>Annular height min (cm)</td>
<td>0.5±0.2</td>
<td>0.4±0.2</td>
<td>0.4±0.3</td>
<td>0.4±0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Annular flexion (cm)</td>
<td>0.3±0.1*</td>
<td>0.2±0.1</td>
<td>0.2±0.1</td>
<td>0.2±0.1</td>
<td>9.9</td>
</tr>
</tbody>
</table>

*=P<0.05 vs. Ischemia by repeated measures ANOVA and Dunnett’s test.

S-L max = maximum septal-lateral annular diameter; S-L min = minimum septal-lateral annular diameter; C-C max = maximum commissure-commissure diameter; C-C min = minimum commissure-commissure diameter; F = F value from repeated measures ANOVA.
tates leaflet coaptation. Thus, loss of annular shortening and flexion associated with ring annuloplasty (particularly rigid rings) is probably deleterious, and, in fact, has been shown to increase leaflet and chordal stress in finite element models. 5

Systolic annular flexion displaces the septal annulus away from the LV outflow tract, assisting ejection. 24 Complete rings may predispose toward LV outflow tract obstruction by flattening the annulus and reducing annular flexion. 25,26 Paneth suture tightening did not reduce annular shortening or flexion compared with the ischemic state, thus preserving the putative advantages of normal annular dynamic motion. Notably, although partial flexible rings abolish septal-lateral and commissure-commissure shortening and freeze the posterior leaflet in the open position, preserved leaflet flexibility would theoretically provide an incremental benefit in compromised hearts by possibly reducing trans-mitral gradients. During systole, sphincteric shortening of the annulus facilitates leaflet coaptation. Thus, loss of annular shortening and flexion associated with ring annuloplasty (particularly rigid rings) is probably deleterious, and, in fact, has been shown to increase leaflet and chordal stress in finite element models. 5

| TABLE 3. Dynamic Motion of the Mitral Leaflets |
|-----------------|-------|-------|------|------|------|
|                  | Control | Ischemia | ASP-1 | ASP-2 | F     |
| \( \theta_{AML} \) max (deg) | 82 ± 8 | 76 ± 8 | 76 ± 8 | 77 ± 9 | 0.8   |
| \( \theta_{AML} \) min (deg) | 36 ± 4 | 34 ± 4 | 35 ± 4 | 36 ± 6 | 1.0   |
| AML excursion (deg) | 46 ± 7 | 42 ± 5 | 41 ± 4 | 41 ± 4 | 1.7   |
| \( \theta_{AML} \) max (deg) | 95 ± 15 | 93 ± 12 | 99 ± 16 | 101 ± 17 | 0.4   |
| \( \theta_{AML} \) min (deg) | 39 ± 14 | 35 ± 8 | 36 ± 11 | 35 ± 12 | 1.0   |
| PML excursion (deg) | 57 ± 9 | 63 ± 12 | 63 ± 12 | 66 ± 11 | 1.2   |

\* = P<0.05 vs. Ischemia by repeated measures ANOVA and Dunnett’s test.

\( \theta_{AML} \) max = maximum anterior mitral leaflet angle; \( \theta_{AML} \) min = minimum anterior mitral leaflet angle; deg = degrees; AML excursion = anterior mitral leaflet excursion; \( \theta_{AML} \) max = maximum anterior mitral leaflet angle; \( \theta_{AML} \) min = minimum anterior mitral leaflet angle; F = F value from repeated measures ANOVA.
position increases the degree of annular reduction required to achieve valve competence, and markedly alters the distribution of systolic closing stress on the leaflets. Increased leaflet stress has been linked to leaflet thickening and collagen deposition that may additionally perturb leaflet motion and closure dynamics. In contrast, Paneth suture tightening, even beyond the amount required to restore mitral competence, had no apparent deleterious impact on either anterior or posterior mitral leaflet excursion.

The mechanism by which annular and leaflet dynamics are preserved after Paneth suture annuloplasty remains undetermined. It has been suggested that annular shortening is abolished by any annuloplasty (whether suture or ring), which reduces annular size below the normal systolic minimum dimension. Standard sizing of semirigid and flexible rings results in the annular septal-lateral and commissure-commissure diameters being smaller than normal. In contrast, septal-lateral and commissure-commissure annular minimal dimensions after both pulls on the Paneth sutures were still greater than the Baseline values (Table 2 and Figure 3). It is possible that the lesser degree of annular reduction required by the Paneth suture annuloplasty allowed preservation of shortening of the mitral annular diameters. Another possible factor favoring annular flexibility is the use of 2 separate Paneth sutures (Figure 2), allowing the anterior and posterior sectors of the annulus to move independently, as opposed to rings (or even a single long suture) that are continuous.

Green et al from this laboratory conjectured that posterior leaflet freezing after semirigid or flexible ring annuloplasty occurs when the lateral annulus is pulled excessively toward the septum and further away from the papillary muscle tips, thereby tethering the leaflet in the open position. In support of this theory, Dagum et al demonstrated that a semirigid (C-E Physio) complete ring markedly displaced the lateral annulus (by 6.9±3.5 mm) toward the septum at end-isovolumic contraction (before ejection began), and the anterolateral papillary muscle moved septally by 3.1±1.6 mm; conversely, a complete flexible (Medtronic Dura) ring displaced the lateral annulus by 4.1±4.7 mm toward the septum at end-isovolumic contraction without dislocating either papillary muscle. Applying that same reference system (origin based on the highest septal marker) to the present dataset revealed that pulling the Paneth annuloplasty sutures moved the lateral annulus closer to the septum by only 3±1 mm without moving the papillary muscles, and the posterior leaflet remained mobile.

Another mechanism maintaining physiological posterior leaflet dynamics after Paneth suture annuloplasty may be residual flexibility of the muscular (or posterior) mitral annulus. Glasson et al demonstrated that semirigid and flexible rings completely abolish shortening of the muscular annular perimeter. On the other hand, compared with the ischemic state, tightening the Paneth sutures had no additional dampening effect on shortening of the muscular annular perimeter. Perhaps this preservation of annular flexibility along the insertion of the posterior leaflet allows the normal complex folding pattern of the closed posterior leaflet to continue, as suggested by finite element models.

**Study Limitations.**
This investigation of acute IMR in open-chest sheep who previously had normal hearts is far different from the clinical scenario of chronic IMR: direct extrapolation of the present findings to the clinical situation is inappropriate. Proximal main circumflex artery occlusion was used in this experiment to create acute myocardial ischemia, an acutely dilated annulus, and acute IMR in order to examine the in vivo effects of Paneth suture annular reduction on annular and leaflet dynamics. We cannot speculate on the durability of this type of suture repair in the clinical setting. As in the similar DeVega tricuspid repair, there is a risk of sutures loosening or tearing out. Nonetheless, demonstrating that annular reduction can be achieved while maintaining physiologic annular flexibility and leaflet motion in this acute, open-chest model may catalyze new studies aimed at designing better mitral reparative techniques. Future studies are required to establish any clinical benefit of preserved annular flexibility suggested by computer and experimental models.

Quantitative measures of MR, such as effective regurgitant orifice and regurgitant volume, have proved useful in studies of chronic IMR, whereas in this experiment, the severity of IMR was only graded subjectively using the conventional clinical semiquantitative scale of 0 to 4+ by the same echocardiographer (DL). The large distance between the esophagus and the heart in sheep resulted in echocardiographic images of suboptimal quality, precluding the calculation of more quantitative measures of the degree of IMR, such as effective regurgitant orifice.

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