Edge-to-Edge Mitral Repair

Tension on the Approximating Suture and Leaflet Deformation During Acute Ischemic Mitral Regurgitation in the Ovine Heart

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Background—Edge-to-edge approximation of the mitral valve leaflets (Alfieri procedure) is a novel surgical treatment for patients with ischemic mitral regurgitation (IMR). Long-term durability may be limited if abnormal mitral leaflet stresses result from this procedure. The aim of the current study was to measure Alfieri stitch tension (F_A) and to explore its geometric determinants in an ovine model of acute IMR as a reflection of the mitral leaflet stresses imposed by the procedure.

Methods and Results—Eight sheep were studied immediately after surgical placement of (1) a force transducer interposed between sutures approximating the central leaflet edges and (2) radiopaque markers around the mitral annulus and leaflet edges. Computer-aided analysis of videofluorograms was used to obtained 3D marker coordinates. Simultaneous measurements of F_A, septal-lateral annular dimension (L_S-L), leaflet edge separation (L_SEP), anterior (L_AL) and posterior (L_PL) leaflet length, and hemodynamic variables were obtained at baseline (CTL) and during acute IMR (circumflex artery occlusion). F_A was significantly elevated throughout the cardiac cycle during IMR compared with CTL, with maximum F_A in diastole (0.26 ± 0.05 versus 0.46 ± 0.08 N, CTL versus IMR; P < 0.05). Multivariable analysis revealed L_S-L as the single independent predictor of maximum F_A (P < 0.001). Positive linear correlations were shown between values of F_A and L_AL and L_PL (dependent variables).

Conclusions—These experimental data demonstrate higher F_A during IMR and cyclic changes in F_A closely paralleling changes in L_S-L, eg, being greatest in diastole when the annulus is largest. Increased F_A during IMR is probably indicative of successful therapeutic intent, but higher diastolic leaflet stresses resulting from persistent or progressive mitral annular dilatation may adversely affect repair durability. This indirectly implies that concomitant mitral ring annuloplasty should be added to the Alfieri repair. (Circulation. 2001;104[suppl I]:I-29-I-35.)

Key Words: mitral valve ▪ valvuloplasty ▪ coronary disease

Mitral valve repair has become the preferred method for correcting ischemic mitral regurgitation (IMR). It provides durable and predictable results in most patients and probably superior clinical outcomes compared with mitral valve replacement. Mitral annuloplasty, with either a prosthetic ring or suture plication, has been applied to correct IMR with the intent of reducing mitral annular area and improving leaflet apposition. Ring annuloplasty has also been shown to prevent IMR in an ovine model of acute LV ischemia, but ring annuloplasty abolishes normal mitral annular dynamics and restricts posterior leaflet mobility. Ring annuloplasty alone, however, can be unpredictable in some patients with IMR.

Recently, a simple mitral valve repair method in which the leading edges of the mitral leaflets are approximated by use of a suture (Alfieri procedure or “bow-tie” repair) was introduced by Alfieri and colleagues. The technique involves short aortic cross-clamp times, and the location of the suture can be customized on the basis of the location of the regurgitant jet with both central and paracommissural leaflet approximation. The procedure has been shown to provide predictable and durable control of MR in patients with a wide spectrum of valvular pathology and was used successfully in a small series of patients with IMR. From theoretical models of the normal mitral valve, it is thought that the tension on the approximating suture between the mitral valve leaflet edges is close to zero. Long-term durability, however, may be limited in mitral valve diseases with preexisting deformation of the mitral valve apparatus if abnormal leaflet stresses result from the procedure.
In evaluating the Alfieri procedure in an ovine model of acute IMR, we hypothesized that mitral annular dilatation during IMR would significantly increase Alfieri stitch tension (F₀) and consequently augment stresses on the mitral valve leaflets. Therefore, the present study was performed to assess F₀ and deformation of the mitral leaflets as a reflection of the mitral leaflet stresses imposed by the procedure and to explore the geometric determinants of F₀ in this experimental setting of acute IMR.

Methods

Surgical Preparation
The surgical procedures used have been previously described.17 Eight adult sheep were used in the study. A diagram of the study protocol is shown in Figure 1. With the chest open but before marker implantation and mitral repair, the proximal circumflex coronary artery was dissected from the surrounding myocardium, and a silicone rubber snare occluder was placed proximal to the first obtuse marginal branch. Doppler echocardiography was used to demonstrate the presence of acute IMR in all animals after a 2-minute occlusion of the proximal left coronary circumflex artery. Subsequently, 8 miniature radiopaque markers were inserted into the subepicardium of the left ventricle along 4 equally spaced longitudinal meridians with 2 levels between the left ventricular (LV) apex and base and 1 marker at the LV apex. After establishment of cardiopulmonary bypass and with the heart arrested, 8 markers were sutured around the mitral annulus, and a silicone rubber snare occluder was placed proximal to the first obtuse marginal branch. Doppler echocardiography was used to document the markers by use of a space-filling multiple tetrahedral volume method.20 Although myocardial volume is included in this calculation of LV volume, it accurately reflects changes in LV chamber size.

Data Acquisition
Videofluoroscopic images were acquired with the animals in the right lateral decubitus position (with the chest open) with a Phillips Optimus 2000 biplane Lateral ARC 2/Poly DIAGNOST C2 system (Phillips Medical Systems, North America) with the image intensifier in the 9-in fluoroscopic mode. Data from the 2 radiographic views were digitized and merged by use of custom-designed software18 to yield the 3D x, y, and z coordinates for each of the radiopaque markers every 16.7 seconds throughout the cardiac cycle. Ascending aortic pressure, LVP, LAP, F₀, and ECG voltage signals were digitized and recorded simultaneously during data acquisition.

Data Analysis

Hemodynamic and Cardiac Cycle Timing
Two or three consecutive steady-state beats during control and after occlusion of the circumflex artery were averaged and defined for each animal as CTL and IMR, respectively. In each cardiac cycle, end systole was defined as the frame containing peak rate of LVP fall (−dP/dt). End diastole was defined as the videofluoroscopic frame containing the peak of the ECG R wave. Instantaneous LV volume at end systole and end diastole was calculated from epicardial LV markers by use of a space-filling multiple tetrahedral volume method.20 Although myocardial volume is included in this calculation of LV volume, it accurately reflects changes in LV chamber size.

Mitrval Annular Dynamics
Mitrval annular area throughout the cardiac cycle was computed from 3D coordinates of the 8 markers sutured around the mitral annulus (markers 1 through 8, Figure 2B). The mitral annulus centroid was first calculated, and then the annular area was divided into 8 individual “pie slices” whose areas were summed to yield total annular area. The septal-lateral mitral annular diameter (L₀) was determined as the distance in 3D space between markers placed on the midseptal (anterior) and midlateral (posterior) mitral annuli (1 through 5 in Figure 2B).

Mitrval Leaflet Dynamics
The anterior and posterior mitral leaflet lengths (L₀ and L₀ respectively) throughout the cardiac cycle were calculated as the 2D distances between the Alfieri stitch at the leaflet edges to the anterior and posterior leaflet bases, respectively (1–13 and 5–13, Figure 2B). Leaflet separation in the 2 newly created mitral orifices was computed as the distance between the respective leaflet edge markers (9–10 and 11–12, Figure 2). L₀ was defined as the average of the distances between the leaflet edge markers in the 2 orifices.
Statistical Analysis

All data are reported as mean±SEM unless otherwise noted. Hemodynamic and marker-derived data from consecutive steady-state beats from each heart were time aligned at end systole. Marker data were calculated from 20 frames before to 20 frames after end systole, a duration of 650 ms. Differences between variables (FA, L_S-L, L_SEP, L_AL, L_PL) during CTL and IMR were compared at end diastole, end systole, peak FA in diastole, and their minimum and maximum by use of a multivariate ANOVA with variables of time, before versus after circumflex artery occlusion, and sheep identification. Statistical significance was inferred if \( P < 0.05 \).

Consecutive diastolic values of the transvalvular pressure gradient (LAP - LVP), L_S-L, L_SEP, and CTL/IMR were entered into a general linear model multivariable analysis with FA as the dependent variable. Because of the variability between animals, analysis was performed for each animal, and tests of significance of the regression coefficients (different from zero) were subsequently performed with the use of the ensemble of data from all experiments. Relationships between L_S-L, L_SEP, and LAP-LVP (independent variables) and FA (dependent variable) with caval occlusion at CTL and during IMR were tested at their maximum in diastole, at time of maximum FA, and at end systole in similar linear regression models. Sheep identification was treated as a model factor to reduce the influence of animal-to-animal variability on the analysis. With the use of linear regression analysis, correlations between values at maximum FA of L_AL and L_PL (dependent variables) and FA (independent variable) during vena caval occlusion at CTL and IMR were tested for each experiment and all experiments together (see above). Statistical models in StatView 227 were used for the analysis.

Results

The average weight of the animals was 68±5 kg. The total duration of cardiopulmonary bypass was 82±9 minutes, with a mean aortic cross-clamp time of 61±7 minutes. Proper marker position and integrity of the leaflet-approximating stitch were confirmed in all animals at postmortem examination (Figure 2A).

Hemodynamics and MR

Hemodynamic variables after the edge-to-edge repair at CTL and during IMR are shown in Table 1. As expected, myocardial ischemia decreased LVP and dP/dt_max and increased LV volumes and mitral annular area at end systole and end diastole. Figure 3 shows the degree of MR for each animal at CTL and IMR before and after the Alfieri procedure. The
location of the regurgitant jet was broadly central and
holosystolic before the Alfieri repair, with some animals
having additional smaller commissural jets. In most animals,
IMR persisted after the repair, and the location of the jet was
predominantly central (on both sides of the approximating
stitch). As indicated by the thin lines in Figure 3, occlusion of
the circumflex artery caused moderate MR in most animals.
Heavy lines demonstrate the change in IMR before and after
the Alfieri procedure. Except for 1 animal that had grade III
MR after the edge-to-edge repair (possibly because of leaflet
distortion from the transducer), the Alfieri procedure in
general had a small effect on the degree of IMR (grade
1.5 ± 0.3 after the Alfieri procedure versus grade 1.8 ± 0.1
before the procedure, P = 0.4). Thus, it is important to note
that in the setting of the Alfieri repair, acute occlusion of the
proximal circumflex artery still resulted in significant IMR in
this ovine preparation. In addition, there was no relationship
between Alfieri stitch tension and the degree of MR during
occlusion of the circumflex artery or between the change in
Alfieri stitch tension and MR from CTL to IMR.

Alfieri Stitch Tension
The time course of F_A, LVP, Ls-L, and LSEP at CTL and IMR
(mean of 8 animals) at steady state and during vena caval
occlusion at CTL and during IMR is shown in Figure 4. F_A
was significantly elevated throughout the cardiac cycle dur-
ing IMR compared with CTL. Differences in F_A between the
2 conditions compared at peak F_A in diastole, at minimum F_A
in early systole, and at end systole were all statistically
significant (Table 2), although the increase in tension was
most remarkable in late systole with maximum F_A increase at
end systole. The change in F_A from end systole to maximum
in diastole was the same during IMR and CTL (0.18 ± 0.02
versus 0.12 ± 0.05 N, P = NS).

| TABLE 1. Hemodynamics and Mitral Annular Dimensions |
|---------------------------------|-----------|-----------|
| CTL | IMR |
| Heart rate, bpm | 95 ± 5 (75–109) | 95 ± 5 (79–118) |
| LVPmax, mm Hg | 121 ± 5 (101–137) | 83 ± 17 (65–121)* |
| LV + dP/dtmax, mm Hg/s | 1.6 ± 0.2 (1.0–2.5) | 0.9 ± 0.2 (0.36–1.48)* |
| LAP – LVPmax, mm Hg | 3.9 ± 0.6 (0.9–6.3) | 2.5 ± 0.6 (0.1–4.2)* |
| LVVEO, mL | 150 ± 9 (116–196) | 177 ± 26 (135–244)* |
| LVVEO, mL | 119 ± 12 (82–172) | 153 ± 13 (125–191)* |
| MAEDO, mm² | 800 ± 70 (580–1060) | 860 ± 50 (670–1130)* |
| MAEOS, mm² | 720 ± 40 (590–890) | 820 ± 50 (650–1040)* |

LW indicates left ventricular volume; ED, end diastole; ES, end systole; LV
+ dP/dtmax = maximum rate of LVP rise; and MAA, mitral annular area. Data are
expressed as mean ± SEM with range (minimum to maximum) in parentheses.
*P < 0.05 vs CTL by t test for paired observations.
Correlates of Alfieri Stitch Tension

The time course of $F_A$ at CTL and IMR was closely related to cyclic changes in $L_{S-L}$. Maximum $F_A$ was found in diastole coincident with maximum $L_{S-L}$, and before maximum $L_{SEP}$. $F_A$ decreased during middiastole before the closing motion of the mitral leaflets. In most hearts, minimum $F_A$ occurred in early systole at the same time as minimum $L_{S-L}$. In 4 animals, the $F_A$ curves in diastole were bimodal with second peaks at end diastole, which explains the observed end-diastolic “humps” in the mean curves. Graphically, the $F_A$ curves closely paralleled changes in $L_{S-L}$ but did not appear to be related to changes in $L_{SEP}$ or the transvalvular pressure gradient. $L_{S-L}$ was also significantly higher during IMR compared with CTL, whereas $L_{SEP}$ was virtually unchanged before and after ischemia. $F_A$ and $L_{S-L}$ decreased during vena cava occlusions at CTL and during IMR, but $L_{SEP}$ remained almost unchanged (Figure 4).

In multivariate linear regression analysis, values of $F_A$ in diastole (versus corresponding values of $L_{S-L}$, $L_{SEP}$, and LAP–LVP) were significantly correlated to $L_{S-L}$ (the only statistically significant factor was regression coefficient, $\beta$=0.014 to 0.086 N/mm; $R^2$=0.54 to 0.97; $P<0.05$ in all animals). Multivariate linear regression analysis of relationships between maximum $L_{S-L}$, $L_{SEP}$, and LAP–LVP (independent variables) and maximum $F_A$ (dependent variable) during steady state and vena cava occlusions at CTL and IMR showed that maximum $L_{S-L}$ was the single statistically significant predictor of $F_A$ in all hearts ($P<0.001$).

Values at maximum $F_A$ and at end systole of $L_{S-L}$, $L_{SEP}$, and LAP–LVP (independent variables) at CTL and during IMR (steady state and caval occlusions) were also entered into the model with corresponding values of $F_A$ as the dependent variable. In both analyses, $F_A$ was positively correlated with $L_{S-L}$ and $L_{SEP}$; however, in multivariable tests for each experiment, statistical significance fell out to either of the covariates, which indicates interaction between the factors.

Relation Between Alfieri Stitch Tension and Mitral Leaflet Deformation

Figure 5 illustrates the relationship between $F_A$, $L_{AL}$, and $L_{PL}$ (mean of 8 experiments) from the time of minimum to maximum $F_A$ at CTL and during IMR. Positive statistically significant correlations were demonstrated between maximum $F_A$, $L_{AL}$, and $L_{PL}$ (dependent variables) at CTL and IMR (steady state and caval occlusion) in each experiment ($L_{AL}$ versus $F_A$: $\beta$=3.0 to 39.4 mm/N, $R^2$=0.57 to 0.97, $P<0.05$ in all hearts; $L_{PL}$ versus $F_A$: $\beta$=1.2 to 17.8 mm/N, $R^2$=0.51 to 0.79, $P<0.05$ in all animals, and for all animals together ($P<0.001$).

Discussion

Mitrval valve reconstruction has become the procedure of choice for patients with most forms of mitral regurgitation. The Alfieri edge-to-edge repair as an adjunctive technique to correct IMR may be a valuable addition to the surgeon’s armamentarium for selected patients who otherwise would require more complicated repair techniques or replacement of a morphologically normal valve. Several advantages make the Alfieri repair appealing: As an adjunctive technique for repair of IMR, the Alfieri stitch can reduce the risks associ-
ated with mitral valve replacement in this high-risk population. The Alfieri technique involves short aortic cross-clamp times and can be customized to the location of the regurgitant jet. Our previous ovine studies attributed acute IMR to annular dilatation and leaflet tethering, and most likely, both mechanisms contributed to the genesis of IMR in the current experiment. Although annuloplasty rings prevent acute ovine IMR, the mechanisms responsible for the clinical efficacy of annuloplasty rings in chronic IMR remain incompletely understood. An Alfieri stitch prevents leaflet separation and creates apposition of the mitral leaflets at that site; it can be a valuable “bail-out” procedure when ring annuloplasty fails to correct IMR satisfactorily. The edge-to-edge repair is intended to counteract leaflet tethering and incomplete mitral leaflet coaptation, which is considered to be a mechanism of IMR in patients. In the present study, acute occlusion of the circumflex artery still resulted in significant IMR even after the Alfieri repair, and there was no relationship between the magnitude of Alfieri stitch tension and the success of the repair. It is important to note, however, that the biomechanical approach of this study was not designed to evaluate the efficacy of the procedure in terms of valvular regurgitation (see Study Limitations).

Some cardiac surgeons have been understandably skeptical of the durability of a single-suture repair in an area of apparently high stress in which high systolic pressure gradients, rapid motion of the mitral leaflets in diastole, and alterations of the mitral valve attachments may potentially contribute to increased stresses on the thin valvular leaflet tissue. In this ovine model of acute IMR, LA, was the major predictor of Alfieri stitch tension. Accordingly, the time course of FA, with maximum in diastole, was closely related to cyclic changes in LA. Increased LSA, resulting from annular dilatation during acute ischemia resulted in higher FA compared with CTL, with maximum FA on the order of 16 to 70 g force. In comparison, the maximum systolic tension of a single chorda tendinea is in the range of 80 to 90 g force. Maximum FA occurred before maximum LSEP, but the observed correlation between FA and LSEP at maximum FA in diastole suggests that the opening motion of the mitral leaflets may exert additional stresses on the Alfieri stitch. Mitral annular dynamics during CTL and IMR in this short-term open-chest study are similar to those observed in our previous conscious, closed-chest ovine experiments (7 to 11 days after annular marker implantation) and other published data.

In 10 very ill patients undergoing edge-to-edge mitral valve repair resulting from IMR, Umana et al anticipated that the mitral leaflets are naturally pushed together and that therefore stresses on the approximating stitch would not be excessive in systole when the suture serves mainly to limit the excursion of the leaflets into the left atrium during high LVP. Consequently, they postulated that there would likely be less tension on the leaflet-approximating suture during systole. From a mathematical model of the stresses on the closed mitral valve derived by Arts et al, it was proposed that a decrease in annular diameter caused by insertion of a mitral annuloplasty ring reduces the leaflet surface area exposed to the systolic ventricular pressure and results in decreased tension on the edges of the leaflets and therefore on the suture. In accordance with this theory, the present study demonstrated lower Alfieri stitch tension with no relation to LVP in systole. Greater Alfieri stitch tension was seen in diastole, which was directly related to mitral annular dimensions at CTL and during IMR, indicating that the highest stresses on the mitral leaflets after the Alfieri procedure appear in diastole, and this may, at least in theory, affect the durability of the procedure. It has also been speculated that major stresses on the Alfieri suture may occur secondary to the AV pressure gradient pulling the leaflets apart during valve opening in diastole. In the present study, however, no relationship between the diastolic transvalvular pressure gradient and Alfieri stitch tension was observed, but there appeared to be a minor contribution of mitral leaflet separation to the Alfieri stitch tension.

The data in this experiment demonstrate that higher FA during IMR was associated with increased strain on the mitral leaflets, as if the Alfieri repair results in an anchoring effect that limits further dilatation of the mitral annulus. Conversely, cyclic changes of mitral annular area and septal-lateral mitral annular diameter after the Alfieri procedure at CTL and IMR were comparable to our previous observations in sheep without valve repair. It must be emphasized that the present experiment consists solely of acute IMR in sheep hearts; accurate clinical extrapolation of these results is difficult. Nonetheless, these data suggest that Alfieri stitch tension in conditions in which annular dilatation is part of the pathophysiology, such as in progression of chronic IMR, may become excessively high and in turn have a negative effect on the durability of the procedure. If this is the case, it argues for performing adjunctive procedures on the mitral annulus to relieve these stresses, such as a mitral annuloplasty ring. Indeed, McCarthy et al reported on 4 patients undergoing partial ventriculectomy and the Alfieri repair alone who, despite minimal initial mitral regurgitation, developed substantial mitral insufficiency within several months, probably because of progressive annular dilatation. In current clinical practice, a concomitant ring annuloplasty is recommended by those who use the Alfieri technique extensively.

In conclusion, the present study demonstrated higher Alfieri stitch tension during IMR and cyclic changes in FA with maximum in diastole, which closely paralleled changes in mitral annular septal-lateral dimension. Increased stitch tension during IMR is probably indicative of successful therapeutic intent, but FA certainly is not zero. Hypothetically, any increase in Alfieri stitch tension caused by residual or progressive annular dilatation may adversely affect repair durability.

**Study Limitations**

The major limitations of this study are those inherent in the acute animal model used. The study was based on experiments using acute myocardial ischemia and therefore did not take into account long-term changes, such as LV remodeling and resultant compensatory changes in the mitral subvalvular apparatus. Furthermore, although the extent of myocardial ischemia after circumflex artery occlusion has been shown to be very reproducible, the effect on mitral valve competency is not simple because it involves many components of the...
mitral valvular-ventricular complex.\textsuperscript{23,26} Therefore, these data must be interpreted in the setting of experimental acute IMR and cannot be extrapolated directly to chronic IMR in human subjects. The animals used in this study were anesthetized and studied in open-chest conditions, and no annuloplasty rings were used, all of which limit extrapolation of these experimental results to humans. Anatomical differences between ovine and human mitral leaflets\textsuperscript{23} and annulus\textsuperscript{27} must also be considered.

Because one of the goals of this study was to investigate leaflet and annular dynamics after the edge-to-edge repair, ring annuloplasty was purposely avoided. In addition, the approximating suture was placed centrally in the mitral orifice in all hearts even though prerepair Doppler echocardiography during ischemia revealed IMR with small regurgitant jets directed toward either of the commissures in some animals, findings that might have prompted a repair not located in the center of the valve. It should also be mentioned that performing the edge-to-edge repair and then inducing acute IMR is distinctly different from the clinical situation in which a broad leak may be present all along the leaflet coaptation zone. Furthermore, the presence of a force transducer might have compromised leaflet apposition adjacent to the approximation point and thereby worsened IMR. The lack of other control animals, ie, sheep without any repair (for comparison with normal annular dynamics) or a group with an Alfieri repair in combination with ring annuloplasty, presents further limitations. The mitral annular dynamics observed in the present study are concordant with our previous investigations of ovine mitral annular dynamics.\textsuperscript{17}

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