Alterations in Left Ventricular Torsion and Diastolic Recoil After Myocardial Infarction With and Without Chronic Ischemic Mitral Regurgitation

Frederick A. Tibayan, MD; Filiberto Rodriguez, MD; Frank Langer, MD; Mary K. Zasio, BS; Lynn Bailey, AS; David Liang, MD, PhD; George T. Daughters, MS; Neil B. Ingels, Jr, PhD; D. Craig Miller, MD

Background—Chronic ischemic mitral regurgitation (CIMR) is associated with heart failure that continues unabated whether the valve is repaired, replaced, or ignored. Altered left ventricular (LV) torsion dynamics, with deleterious effects on transmural gradients of oxygen consumption and diastolic filling, may play a role in the cycle of the failing myocardium. We hypothesized that LV dilatation and perturbations in torsion would be greater in animals in which CIMR developed after inferior myocardial infarction (MI) than in those that it did not.

Methods—8±2 days after marker placement in sheep, 3-dimensional fluoroscopic marker data (baseline) were obtained before creating inferior MI by snare occlusion. After 7±1 weeks, the animals were restudied (chronic). Inferior MI resulted in CIMR in 11 animals but not in 9 (non-CIMR). End-diastolic septal-lateral and anterior-posterior LV diameters, maximal torsional deformation (ϕ_{max}, rotation of the LV apex with respect to the base), and torsional recoil in early diastole (ϕ_{r,b} first 5% of filling) for each LV free wall region (anterior, lateral, posterior) were measured.

Results—Both CIMR and non-CIMR animals demonstrated derangement of LV torsion after inferior MI. In contrast to non-CIMR, CIMR animals exhibited greater LV dilation and significant reductions in posterior maximal torsion (6.1±4.3° to 3.9±1.9°* versus 4.4±2.5° to 2.8±2.0°; mean±SD, baseline to chronic, *P<0.05) and anterior torsional recoil (−1.4±1.1° to −0.2±1.0° versus −1.2±1.0° to −1.3±1.6°).

Conclusion—MI associated with CIMR resulted in greater perturbations in torsion and recoil than inferior MI without CIMR. These perturbations may be linked to more LV dilation in CIMR, which possibly reduced the effectiveness of fiber shortening on torsion generation. Altered torsion and recoil may contribute to the “ventricular disease” component of CIMR, with increased gradients of myocardial oxygen consumption and impaired diastolic filling. These abnormalities in regional torsion and recoil may, in part, underlie the “ventricular disease” of CIMR, which may persist despite restoration of mitral competence. (Circulation. 2004;110[suppl II]:II-109–II-114.)

Key Words: myocardial infarction ■ mitral valve ■ mechanics

Chronic ischemic mitral regurgitation (CIMR) is an important complication after myocardial infarction (MI) and is linked to increased mortality that is independent of the degree of underlying left ventricular (LV) dysfunction.1 Repairing or replacing the valve fails to change the mortality curve dramatically, suggesting that the primary problem lies in the myocardium.2 Supporting this idea, changes in LV geometry, such as LV diameter) has been linked to decreases in LV systolic torsion and early diastolic recoil, which, in turn, likely contribute to a cycle of progressive LV functional decline.

We surmised that derangement in torsion might play a role in the “ventricular disease” element of CIMR. Therefore, we tested the hypotheses that inferior MI is associated with alterations in torsion and recoil, and that these postinfarct alterations would be greater in animals in which CIMR developed than in those in which CIMR did not develop.
LV chamber through the apex. A micromanometer pressure was titrated to maintain coronary perfusion pressure (aortic diastolic)

Surgical Preparation
Forty Dorset hybrid sheep (71 ± 5 kg; R.E. McGrew Livestock, Dixon, Calif) were premedicated with ketamine (25 mg/kg intramuscular), and anesthesia was induced with sodium thiopental (6.8 mg/kg intravenous) and maintained with inhalation isoflurane (1 to 2.5%). Through a left thoracotomy, 8 tantalum myocardial markers (2 to 9; Figure 1) were inserted in the LV epicardial layer along 4 equally spaced longitudinal meridians, with 1 marker (1) at the LV apex. Polypropylene 2-0 sutures were passed loosely around the 1, 2, or, occasionally, 3 obtuse marginal branches of the left circumflex coronary artery located between the posterior vein of the left ventricle and the middle cardiac vein, and loosely snared using the method of Llaneras et al.6 On cardiopulmonary bypass, tantalum markers (6 to 9; Figure 1), z-axis passing through the centroid of the coronary valve is shown for reference. One marker (1) is placed at the apex, with markers placed around 4 meridians (anterior, lateral, posterior, septal) at 2 levels, apical (2 to 5) and basal (6 to 9).

Methods

After 7 ± 1 weeks, the animals were returned to the cardiac catheterization laboratory for recording of hemodynamic, transesophageal echocardiography, and marker data. MR was graded based on regurgitant jet extent and width as none (0), trace (+0.5), mild (+1), moderate (+2), moderate–severe (+3), or severe (+4) by an experienced echocardiographer (D.L.) using a 3-chamber view (approximately equivalent to the vertical plane in a human study).

All animals received humane care in compliance with the Principles of Laboratory Animal Care formulated by the National Society for Medical Research and the Guide for Care and Use of Laboratory Animals prepared by the National Academy of Sciences and published by the National Institutes of Health (DHEW NIH publication 85-23, revised 1985). This study was approved by the Stanford University Medical School Laboratory Research Animal Review committee and conducted according to Stanford University policy.

Data Acquisition
Images were acquired with the animal in the right lateral position with a biplane videofluoroscopy system (Philips Medical Systems, North America Company). Data from 2 radiographic views were digitized and merged to yield 3-dimensional coordinates for each of the radio-opaque markers every 16.7 ms using custom-designed software. Ascending aortic pressure, LV pressure, and electrocardiogram voltage signals were digitized and recorded simultaneously at end-expiration during marker data acquisition. Koningsberg catheters were calibrated using micromanometer pressure transducers (Millar Instruments, Inc) temporarily placed during the study.

Data Analysis
Ten animals died postoperatively, primarily of respiratory complications after cardiopulmonary bypass. Of the 30 animals that underwent coronary occlusion, 10 died acutely secondary to refractory ventricular arrhythmias. The remaining 20 animals were divided into 2 groups on the basis of severity of MR at the time of the second study: 9 did not have MR (MR < 1.5; “non-CIMR” group), and 11 had chronic ischemic MR (MR ≥ 2; “CIMR” group).

Hemodynamics and Cardiac Cycle Timing
Three consecutive steady-state beats before infarction were averaged and defined as “baseline” data for each animal. Similarly, at the follow-up study, 3 beats were averaged and termed “chronic” data. During each cardiac cycle, end-systole was defined as the time of the videofluoroscopic frame containing the point of peak negative rate of LVV was calculated from the positions of the epicardial LV markers and annular markers using a space-filling multiple tetrahedral volume method for each frame, i.e., every 16.7 ms.

Regional fractional area shortening was determined as follows. The LV and annular markers were used to divide the ventricle into 4 longitudinal (anterior, lateral, posterior, and septal) regions and 3 circumferential (basal, equatorial, and apical) levels (Figures 1 and 3). Fractional area shortening for each region was calculated as the ratio of end-diastolic area to end-systolic area.

Computation of LV Torsion
At each sample time, all marker Cartesian 3-dimensional coordinates (x, y, and z) were transformed into an internal cylindrical coordinate system (r, θ, and z) with origin at the centroid of the basal LV markers (6 to 9; Figure 1), z-axis passing through the centroid of the markers defining the apical transverse LV plane (2 to 5; Figure 1), and with 0° reference passing through the anterior LV basal marker (6; Figure 1). Positive angles were defined as counterclockwise as viewed from apex to base.

Epicardial marker m (2 to 5; Figure 1) for each apical level, b (b=b1, b2, b3; from EDL to EDs1) during each beat, and torsional deformation φmb(t) at each sample time t (t=0@EDL, 1, 2, . . . , T@EDs1) were computed as:

\[ \phi_{mb}(t) = \theta_{mb}(t) - \theta_{mb}(T) \]

After 7 ± 1 weeks, the animals were returned to the cardiac catheterization laboratory for recording of hemodynamic, transesophageal echocardiography, and marker data. MR was graded based on regurgitant jet extent and width as none (0), trace (+0.5), mild (+1), moderate (+2), moderate–severe (+3), or severe (+4) by an experienced echocardiographer (D.L.) using a 3-chamber view (approximately equivalent to the vertical plane in a human study).

All animals received humane care in compliance with the Principles of Laboratory Animal Care formulated by the National Society for Medical Research and the Guide for Care and Use of Laboratory Animals prepared by the National Academy of Sciences and published by the National Institutes of Health (DHEW NIH publication 85-23, revised 1985). This study was approved by the Stanford University Medical School Laboratory Research Animal Review committee and conducted according to Stanford University policy.

Data Acquisition
Images were acquired with the animal in the right lateral position with a biplane videofluoroscopy system (Philips Medical Systems, North America Company). Data from 2 radiographic views were digitized and merged to yield 3-dimensional coordinates for each of the radio-opaque markers every 16.7 ms using custom-designed software. Ascending aortic pressure, LV pressure, and electrocardiogram voltage signals were digitized and recorded simultaneously at end-expiration during marker data acquisition. Koningsberg catheters were calibrated using micromanometer pressure transducers (Millar Instruments, Inc) temporarily placed during the study.

Data Analysis
Ten animals died postoperatively, primarily of respiratory complications after cardiopulmonary bypass. Of the 30 animals that underwent coronary occlusion, 10 died acutely secondary to refractory ventricular arrhythmias. The remaining 20 animals were divided into 2 groups on the basis of severity of MR at the time of the second study: 9 did not have MR (MR < 1.5; “non-CIMR” group), and 11 had chronic ischemic MR (MR ≥ 2; “CIMR” group).

Hemodynamics and Cardiac Cycle Timing
Three consecutive steady-state beats before infarction were averaged and defined as “baseline” data for each animal. Similarly, at the follow-up study, 3 beats were averaged and termed “chronic” data. During each cardiac cycle, end-systole was defined as the time of the videofluoroscopic frame containing the point of peak negative rate of LVV was calculated from the positions of the epicardial LV markers and annular markers using a space-filling multiple tetrahedral volume method for each frame, i.e., every 16.7 ms.

Regional fractional area shortening was determined as follows. The LV and annular markers were used to divide the ventricle into 4 longitudinal (anterior, lateral, posterior, and septal) regions and 3 circumferential (basal, equatorial, and apical) levels (Figures 1 and 3). Fractional area shortening for each region was calculated as the ratio of end-diastolic area to end-systolic area.

Computation of LV Torsion
At each sample time, all marker Cartesian 3-dimensional coordinates (x, y, and z) were transformed into an internal cylindrical coordinate system (r, θ, and z) with origin at the centroid of the basal LV markers (6 to 9; Figure 1), z-axis passing through the centroid of the markers defining the apical transverse LV plane (2 to 5; Figure 1), and with 0° reference passing through the anterior LV basal marker (6; Figure 1). Positive angles were defined as counterclockwise as viewed from apex to base.

Epicardial marker m (2 to 5; Figure 1) for each apical level, b (b=b1, b2, b3; from EDL to EDs1) during each beat, and torsional deformation φmb(t) at each sample time t (t=0@EDL, 1, 2, . . . , T@EDs1) were computed as:

\[ \phi_{mb}(t) = \theta_{mb}(t) - \theta_{mb}(T) \]
and mean LV torsional deformation \( \phi(t) \) for the 3-beat sequences comprising each run in each heart as:

\[
\phi(t) = \frac{\phi_{\text{an}}(t) + \phi_{\text{lat}}(t) + \phi_{\text{post}}(t)}{3}
\]

Fractional ejection (FRAC) at each sample time (t) for each beat (b) was defined as follows:

\[
\text{FRAC}(t) = \frac{\text{LVV}_{\text{EDVb}}(t)/\text{LVV}_{\text{EDVb}}}{\text{LVV}_{\text{EDVb}} - \text{LVV}_{\text{EDVb}}(t)}/3
\]

where \( \text{LVV}_{\text{EDVb}}(t) \) is LVV at time t, \( \text{LVV}_{\text{EDVb}} \) is LVV at EDV, and \( \text{LVV}_{\text{EDVb}} \) is LVV at end-ejection for beat b. Mean fractional ejection at each sample time (t) \( \text{FRAC}(t) \) for the 3-beat sequences comprising each run in each heart was as follows:

\[
\text{FRAC}(t) = \frac{\text{FRAC}^1(t) + \text{FRAC}^2(t) + \text{FRAC}^3(t)}{3}
\]

For each LV free wall region (anterior, lateral, posterior), \( \phi(t) \) was characterized by maximum LV torsional deformation \( \phi_{\text{max}} \), and early diastolic torsional recoil \( \phi(t) \) as the change in torsional deformation from end ejection to the first 5% of LV filling.

### Results

Table 1 summarizes hemodynamics at baseline and 7 weeks after inferior MI (chronic) in the non-CIMR and CIMR groups. Both CIMR and non-CIMR hearts exhibited reduced LV maximum dp/dt and increased end-diastolic volume index over the 7-week interval. The CIMR group exhibited increased time constant of diastolic pressure relaxation (\( \tau \)) after infarction. Left-ventricular end-diastolic pressure also increased slightly in the CIMR.

Table 2 summarizes regional torsion dynamics at baseline and 7 weeks after inferior MI in the non-CIMR and CIMR groups. Seven weeks after inferior MI, both groups exhibited increased maximum systolic torsion \( \phi_{\text{max}} \) in the anterior LV region and decreased systolic torsion in the lateral ventricle. In the CIMR animals, systolic torsion was also decreased significantly in the posterior wall. Both CIMR and non-CIMR hearts had decreased early diastolic torsional recoil \( \phi(t) \) in the lateral and posterior LV walls, but decreased recoil in the anterior LV was evident only in the CIMR animals. Figure 2 illustrates these torsion dynamics in one of the CIMR hearts in this study.

Table 3 summarizes end-diastolic septal-lateral and antero-posterior LV dimensions at the basal and apical levels. After inferior MI, non-CIMR animals had significant dilation of the LV walls.

### Statistical Analysis

All data are reported as mean±SD. Changes in the CIMR and non-CIMR groups from baseline to chronic were analyzed using Student t test for paired comparisons. Changes from baseline to chronic conditions between the CIMR and non-CIMR groups were compared using a t test for unpaired comparisons.

### Table 1. Hemodynamics

<table>
<thead>
<tr>
<th></th>
<th>Non-CIMR</th>
<th>CIMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR (0–4+), mm Hg</td>
<td>0.6±0.2</td>
<td>0.9±0.2</td>
</tr>
<tr>
<td>LV dp/dtmax, mm Hg</td>
<td>192±440</td>
<td>1604±512*</td>
</tr>
<tr>
<td>tau, ms</td>
<td>35±4</td>
<td>35±4</td>
</tr>
<tr>
<td>LVEDP, mm Hg</td>
<td>18±4</td>
<td>20±4</td>
</tr>
<tr>
<td>EDVI, mL/m²</td>
<td>71±11</td>
<td>83±16*</td>
</tr>
</tbody>
</table>

MR indicates mitral regurgitation; LV dp/dtmax, maximum of first derivative of pressure vs time; tau, \( \tau \), time constant of diastolic pressure relaxation; LVEDP, LV pressure at end-diastole; EDVI, end-diastolic volume index.

*P<0.05 vs baseline.
†P<0.05 change from baseline in non-CIMR vs change from baseline in CIMR.

### Table 2. Regional LV Torsion Dynamics

<table>
<thead>
<tr>
<th></th>
<th>Non-CIMR</th>
<th>CIMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior ( \phi_{\text{max}} ), °</td>
<td>3.8±3.3</td>
<td>0.6±0.6*</td>
</tr>
<tr>
<td>Anterior ( \phi(t) ), °</td>
<td>0.8±0.4</td>
<td>1.2±0.5</td>
</tr>
<tr>
<td>Latera ( \phi_{\text{max}} ), °</td>
<td>2.5±2.5</td>
<td>2.0±2.3*</td>
</tr>
<tr>
<td>Lateral ( \phi(t) ), °</td>
<td>1.1±1.1</td>
<td>0.4±1.0*</td>
</tr>
<tr>
<td>Posterior ( \phi_{\text{max}} )</td>
<td>3.7±4.3</td>
<td>3.9±1.9*</td>
</tr>
<tr>
<td>Posterior ( \phi(t) ), °</td>
<td>3.7±2.1</td>
<td>0.7±1.9*</td>
</tr>
</tbody>
</table>

\( \phi_{\text{max}} \) indicates maximum systolic torsion; \( \phi(t) \), torsional recoil during first 5% of diastolic filling.

*P<0.05 vs baseline.

### Table 3. End-Diastolic LV Basal and Apical Diameters

<table>
<thead>
<tr>
<th></th>
<th>Non-CIMR</th>
<th>CIMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal S-L, cm</td>
<td>5.2±1.0</td>
<td>5.4±0.9</td>
</tr>
<tr>
<td>Basal A-P, cm</td>
<td>4.9±1.4</td>
<td>5.2±1.7*</td>
</tr>
<tr>
<td>Apical S-L, cm</td>
<td>5.2±0.5</td>
<td>5.1±1.0</td>
</tr>
<tr>
<td>Apical A-P, cm</td>
<td>3.5±0.7</td>
<td>3.6±0.5</td>
</tr>
</tbody>
</table>

S-L indicates septal-lateral; A-P, anterior-posterior.

*P<0.05 vs baseline.
†P<0.05 change from baseline in non-CIMR vs change from baseline in CIMR.
endocardial oxygen demand and a higher ratio of endocardial
shortened less (0.10
Removing torsion from the model, the epicardial sarcomeres
reported in dilated cardiomyopathy4 and chronic (noniche-
gradients of fiber strain and oxygen consumption, has been
transmural gradients of fiber strain and oxygen demand.8,9
Systolic torsion, a wringing motion as the apex rotates with
the apical level of the lateral and anterior walls.
CIMR group only, fractional area shortening was increased at
both basal and apical levels. The change from baseline in
the CIMR was also significantly greater than that of the
non-CIMR in both axes at the apical level, and in the
diastolic recoil occurs during isovolumic relaxation. Such recoil,
that region. By the same token, the increased torsion in the
anterior-posterior diameter at the basal level, whereas CIMR
hearts dilated in the septal-lateral and anterior posterior axes
at both basal and apical levels. The change from baseline in
the CIMR was also significantly greater than that of the
non-CIMR in both axes at the apical level, and in the
septal-lateral dimension at the basal level.
Figure 3 summarizes regional fractional area shortening for
non-CIMR and CIMR animals before (upper line in box) and 8
weeks after (lower line in box) MI. In both CIMR and
non-CIMR groups, fractional area shortening was reduced at
the basal, equatorial, and apical levels for the lateral wall, and
basal and equatorial levels for the posterior wall, approxi-
mately corresponding to the targeted area of the infarct. In
both groups, fractional area shortening was increased at the
equatorial and apical levels of the septal wall, but in the
CIMR group only, fractional area shortening was increased at
the apical level of the lateral and anterior walls.
Discussion
Both CIMR and non-CIMR animals had LV dilation and
derangement in systolic torsion and diastolic recoil after
inferior MI. The CIMR animals, moreover, exhibited signif-
ificant reductions in posterior maximal torsion and anterior
torsion recoil not evident in non-CIMR. These data, compar-
ing regional torsion dynamics in CIMR with a postinfarct
control group without CIMR, may provide important insights
into the “ventricular disease” of CIMR.
Systolic Torsion
Systolic torsion, a wringing motion as the apex rotates with
respect to the base about the LV long axis, minimizes
transmural gradients of fiber strain and oxygen demand.8,9
Decreased systolic torsion, which should increase these
gradients of fiber strain and oxygen consumption, has been
reported in dilated cardiomyopathy4 and chronic (nonische-
mic) MR,7 possibly contributing to a cycle of progressive
myocardial functional decline.
In a mathematical model studying the effects of torsion,
normal torsion resulted in sarcomere shortening ranging from
0.20 μm at the epicardium to 0.48 μm at the endocardium.
Removing torsion from the model, the epicardial sarcomeres
shortened less (0.10 μm) and the endocardial sarcomeres
shortened more (0.55 μm), thus increasing the transmural
gradient of shortening.10 This corresponded to increased
endocardial oxygen demand and a higher ratio of endocardial
to epicardial oxygen demand (1.08 versus 1.29).10 That study
and others8 suggest that decreased torsion leads to a less
efficient state in which the endocardium performs a greater
share of the work of the ventricle. In the present study,
inferior MI resulted in increased anterior wall torsion and
decreased lateral wall torsion in both CIMR and non-CIMR
animals. In the CIMR animals, torsion was also reduced in
the posterior region after infarction. Decreased torsion in the
lateral LV wall (and posterior wall in the case of the CIMR
group) may result from contractile dysfunction in this region
after the postero-lateral infarction (Figure 3). Decreased
contractility causes less local force giving rise to torsion in
that region. By the same token, the increased torsion in the
anterior region may be related to compensatory hypercon-
tration in the septum and anterior LV wall in the CIMR. It may
also result in part from a change in the material properties of
the adjacent (lateral and posterior) myocardium after infar-
cation that unloads the anterior region.
Reductions in systolic torsion, observed in the non-CIMR
hearts in the lateral region and the CIMR hearts in both the
posterior and lateral regions, would be expected to increase
transmural gradients of fiber strain and oxygen demand in
these regions, placing a relatively greater burden on the
endocardial fibers. Even though the changes in torsion seen in
this study are small, the deleterious effects may add up over the
course of time and serve to compound the probably
greater insults caused by increased wall stress in these
already-compromised ventricles. Failure to modulate these
mechanical and metabolic gradients may contribute to a
vicious cycle of ventricular failure and functional decline
observed in CIMR that persists even if the valve is repaired or
replaced.
Specifically, decreased torsion, decreased contractile func-
tion, and LV dilatation may further compromise myocardial
contraction and lead to progressive LV dilatation by increas-
ing the burden on the already-dysfunctional (and relatively
hyperperfused) endocardium.
Diastolic Recoil
Studies of normal hearts indicate that the bulk of torsional
recoil occurs during isovolumic relaxation. Such recoil,
which is linked to the rapid release of restoring forces in the
extracellular matrix and to the relaxation and relengthening of
contracted sarcomeres, is a likely determinant of myocardial
compliance during isovolumic relaxation and a contributor to
diastolic LV suction, which may enhance filling.11

The restoring forces contributing to diastolic suction may
occur when end-systolic volume decreases below V_{es}, the
equilibrium volume of the ventricle, which is more likely to
occur under increased inotropic states (which decrease ESV
and increase V_{es}). Restoring forces may also be released in
response to the deformation of the 3-dimensional extracellular
matrix and sarcomeric proteins such as titin.11 Torsion has
been considered an important deformation leading to such
restoring forces. Similarly, the widespread perturbations in
torsional recoil observed in this study suggest that loss of
recoil may contribute to impaired diastolic LV suction in
CIMR. This loss of recoil may be related to increased τ, as
observed in this study. In a magnetic resonance imaging study
of dogs, Dong et al showed that the rate of torsional recoil
was an excellent predictor of LV relaxation through a variety
of hemodynamic states and loading conditions.12

LV Dilation

LV dilation has been shown to be a powerful predictor of
systolic function and survival in patients after MI.3 Although
LV dilation in CIMR may exert many of its deleterious
effects on ventricular performance through increased wall
stress,13 the consequences of LV dilation, which were greater
in the CIMR than the non-CIMR, on systolic torsion and
recoil may also contribute to decreased ventricular function.

To see how increasing LV diameters might affect torsion,
consider that the net moment giving rise to torsion can be
modeled as the sum of opposing subendocardial and subepi-
cardial vectors, each proportional to the length of its lever
arm. Thus, although the angles of inclination of the suben-
docardial and subepicardial fibers are approximately equal
(but opposite in sign), physiological torsion during systole is
dominated by the subepicardial fibers because of their larger
radii (and longer lever arms).14 Ventricular dilatation tends to
increase the radii of both the subendocardial and subepicar-
dial layers, thus allowing a relatively greater contribution from
the subendocardium to the net torsion moment and
decreasing maximum torsion. Taber et al predicted such a
result by reasoning that if eccentric hypertrophy, the epicar-
dial fibers would lose some of their mechanical advantage.8
Similarly, during early diastole, torsional recoil should be
driven by the release of restoring forces in the extracellular
matrix and myofibers of the subepicardium, which relax
before those of the subendocardium. The relative equalization
of the subendocardial and subepicardial lever arms again
reduces the net torsional moment, decreasing early diastolic
recoil, which may be important for LV filling at low pres-
ses. Changes in the extracellular matrix after inferior MI
mediated by matrix metalloproteinases15 may also affect the
explosive release of restoring forces in early diastole.

Effect of Infarct Size

Despite our best efforts to induce infarctions of similar size
and location,6 individual variations in coronary anatomy
among the sheep contributed to different size infarctions that
presumably affected outcome. Smaller infarctions resulted in
lesser ventricular dilation without CIMR, larger infarctions
resulted in greater ventricular dilation associated with CIMR,
and very large infarctions resulted in acute LV failure,
arrhythmias, and death. The size of the infarct affected the
amount of remaining contracting myocardium and thus may
underlie the observed alterations in torsion. Using a similar
ovine model of CIMR, Guy et al demonstrated that prophy-
lactic ring annuloplasty (before infarction) could prevent
IMR, but not secondary LV dilation. This again indicates that
the size of the infarction, not the MR per se, may be the
primary pathologic culprit responsible for adverse LV remodel-
ing. The alterations in torsion observed in this study are
dependent to some extent on infarct size in addition to degree
of CIMR.

CIMR has been called a “ventricular disease” marked by
continuing LV dilatation, worsening contractile function, and
poor survival, whether the incompetent valve is replaced,
repaired, or ignored.2 After MI, LV dilation and contractile
dysfunction lead to alterations in torsion and recoil that may
result in increased gradients of oxygen demand and ventric-
ular dysfunction. Thus, abnormalities in torsion may contrib-
ute to a persistent cycle of ventricular decline if such LV
dilation is not addressed at the time of surgery. Although the
changes in torsion may be more a function of infarct size
rather than CIMR itself, these data suggest for the first time
to our knowledge that alterations in torsion and recoil may
play a part in the persistent systolic and diastolic dysfunction
observed in CIMR. It remains to be seen whether procedures
designed to remodel the LV (undersized annuloplasty,13
Acorn,16 or surgical ventricular restoration17) by decreasing
LV radii of curvature or end-systolic volume will have a
long-term effect on torsion or LV dysfunction in patients with
CIMR.

Limitations

This study used a model of ovine chronic inferior infarction
that differs from the clinical entity. The sheep have all
undergone opening of the pericardium, cardiopulmonary
bypass, and surgical manipulation of the mitral apparatus.
Also, differences in ventricular and coronary anatomy be-
tween sheep and humans may influence the remodeling in
chronic infarction and the distortions in systolic torsion and
diastolic recoil. It is unknown whether reduction of CIMR
would restore normal torsion dynamics. Studies are currently
underway to investigate this hypothesis, but correction of
torsion would probably require addressing both the LV
dilation and the contractile dysfunction induced by the
infarct.

Acknowledgments

The authors gratefully acknowledge the superb technical assistance
provided by Carol W. Mead, Maggie Brophy, Katha Gazda, and
Mark Grisedale.

References

1. Grigioni F, Enriquez-Sarano M, Zehr KJ, et al. Ischemic mitral regurgi-
tation: long-term outcome and prognostic implications with quantitative
74:1481.


Alterations in Left Ventricular Torsion and Diastolic Recoil After Myocardial Infarction With and Without Chronic Ischemic Mitral Regurgitation
Frederick A. Tibayan, Filiberto Rodriguez, Frank Langer, Mary K. Zasio, Lynn Bailey, David Liang, George T. Daughters, Neil B. Ingels, Jr and D. Craig Miller

doi: 10.1161/01.CIR.0000138385.05471.41
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2004 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/110/11_suppl_1/II-109

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/