Post-systolic shortening of ischemic myocardium – a mechanism of abnormal intraventricular filling

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Running head: Post-systolic shortening and abnormal LV filling

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**Abstract**

**Background and aims:** Acute myocardial ischemia has been associated with abnormal filling patterns in the left ventricular (LV) apex. We hypothesized that this may in part be due to post-systolic shortening of ischemic apical segments that leads to reversal of early-diastolic apical flow.

**Methods:** Fourteen open-chest anesthetized dogs were instrumented with micromanometers in the LV apex and the left atrium, and myocardial sonomicrometers in the anterior apical LV wall. Intraventricular filling by color Doppler and wall motion by SDE were assessed from an apical view. Measurements were taken before and after 5 minutes of LAD occlusion. In 4 of the dogs we measured the pressure difference between LV apex and outflow tract.

**Results:** At baseline peak early-diastolic flow velocities in the distal 1/3 of the left ventricle were directed towards apex (9.2 ± 1.6 cm/s). Following LAD occlusion the velocities reversed (-2.3 ± 0.4 cm/s, \( P<0.01 \)), indicating that blood was ejected from the apex towards the base during early filling. This interpretation was confirmed by wall motion analysis, which showed post-systolic shortening of apical myocardial segments. The post-systolic shortening represented 9.7 ± 1.7 % (\( P<0.01 \)) and 14.2 ± 2.4 % (\( P<0.01 \)) of end-diastolic segment length by SDE and sonomicrometry, respectively. Consistent with the velocity changes, we found reversal of the early diastolic pressure gradient from the LV apex to outflow tract.

**Conclusion:** In the present model acute LAD occlusion resulted in reversal of early-diastolic apical flow and this was attributed to post-systolic shortening of dyskinetic apical segments. The clinical diagnostic importance of this finding remains to be determined.
Key words: strain Doppler echocardiography, 2-D color Doppler, myocardial ischemia,

diastolic filling
**Introduction**

Assessment of LV intracavitary filling by Doppler echocardiography is one of several non-invasive approaches for studying LV diastolic function. In the normal left ventricle the initial intraventricular filling wave propagates rapidly towards the apex, and as demonstrated by color M-mode Doppler there is near simultaneous onset of filling velocities along the entire LV inflow tract (7). However, in patients with reduced LV ejection fraction or impaired diastolic function, the early-diastolic apical filling may be markedly delayed, and this can be measured as slowing of mitral-to-apical flow propagation (13, 1). This has been attributed to a decrease in rate of LV relaxation, which causes a decrease in the driving pressure for mitral-to-apical flow (13, 1, 12), to loss of “apical suction” (12) and enhanced vortex formations due to changes in LV and mitral valve geometry (10).

There is, however, very limited insight into how regional wall motion interacts with intraventricular flow. A common finding in ischemic myocardium is post-systolic (post-ejection) shortening, and consequently delayed onset of diastolic lengthening (17, 16, 8). Therefore, in the ischemic ventricle there may be substantial regional asynchrony in onset of myocardial diastolic lengthening, and this in turn may have an impact on intraventricular flow. The paucity of data regarding interactions between regional function and intraventricular filling reflects the limited ability of current imaging modalities to quantify regional myocardial function throughout the different phases of the cardiac cycle. We have recently demonstrated that strain Doppler echocardiography (SDE) represents a non-invasive method to quantify regional function (18). In this regard SDE appears superior to conventional tissue Doppler imaging (TDI) which is strongly influenced by function in neighboring segments and translational effects. Therefore, SDE in
combination with color flow imaging may represent a method to study interactions between intraventricular flow and regional wall motion.

The present study was designed to investigate how wall motion abnormalities in ischemic myocardium interact with intracavitary filling, and the main objective was to determine if post-systolic shortening of ischemic apical segments may lead to reversal of early-diastolic apical flow. The study was done in a dog model and sonomicrometry was used as a reference method for regional myocardial function.

**Methods**

Fourteen dogs of either sex and average body weight 21.2 kg were given thiopentone 25 mg/kg b.w. and morphine 100 mg IV, followed by infusion of morphine 50 - 100 mg/h IV and pentobarbital 50 mg IV every hour. The animals were artificially ventilated through auffed endotracheal tube using room air with 20 - 50 % oxygen. A limb lead was monitored. After a median sternotomy, the pericardium was split from apex to base and the edges of the pericardial incision were loosely resutured. Inflatable vascular occluders were placed around the proximal one third of the LAD. The dog was placed in the right supine position during recordings. The study was approved by the National Animal Experimentation Board.
**Pressure measurements**

Via a carotid artery with fluoroscopic guidance we placed a 5F micromanometer-tipped catheter (Model MPC-500, Millar Instruments, Houston, TX) in the LV apical region. Via the appendage a 5 F micromanometer and a fluid filled catheter were placed in the left atrium. In 4 of the dogs another 5F catheter was positioned in the LV outflow tract just proximal to the aortic valve. All pressure transducers were calibrated with a mercury manometer. The pressures were zero-referenced against the fluid filled left atrial (LA) catheter. Pressure and ECG data were processed via preamplifiers and were digitized at 200 Hz for further analysis on a PC computer station.

**Sonomicrometry**

One pair of ultrasonic crystals was implanted in the inner one half of the myocardium in the anterior LV wall near the apex, aligned parallel with the LV long axis. In 4 of the dogs another pair of crystals was implanted in a non-ischemic region in the anterolateral wall near the base, in the perfusion territory of the left circumflex artery (Cx). The crystals were connected to a sonomicrometer (Triton Technology Inc., San Diego, Ca, USA or Sonometrics, London, Ontario, Canada).

**Strain Doppler echocardiography**

The method has previously been described in detail (18). Using a combined tissue imaging (3.5 MHz) and Doppler (2.75 MHz) transducer (GE Vingmed Ultrasound, Horten, Norway) we recorded images from an apical view with a frame rate varying from 65 to 106 (mean value 88 frames per second). Strain rate was calculated as the Doppler velocity gradient between two points with a distance of 8 mm and strain was calculated as the time
integral of strain rate (18). An experimental application programmed in Microsoft Visual C++ (Microsoft Corp., Redmond, WA, USA) was used to extract strain along an M-mode line which was oriented in the direction from apex to base.

2-D color Doppler echocardiography:
Both 2-D color and strain Doppler echocardiography were recorded from a modified apical 2 chamber view, by orienting the 2-D image planes through the regions in which we had inserted the segment length crystals; i.e. the anterolateral wall near the apex.

The low velocity filter was set in the range of 1-4 cm/sec with a frame rate varying from 38 to 90 (mean value 58 frames per second). The digital color velocity data were transferred to an external computer (Macintosh, Apple Computer Inc.) and analyzed by the use of a dedicated analysis program (Echopac, GE Vingmed Ultrasound).

Experimental protocol:
Recordings were first taken at baseline. Then we inflated the LAD occluder for a median of 5 minutes and did recordings during ischemia. Because of interference, sonomicrometry and Doppler echocardiography could not be measured simultaneously. During baseline and during ischemia we first recorded pressures, ECG and Doppler flow velocities during 10 seconds and then pressures, ECG and myocardial segment length during the subsequent 10 seconds. Since it was not feasible to measure 2-D color flow and strain by Doppler simultaneously, we did the strain Doppler recordings close (within 2 minutes) to the color flow measurements.
At the end of each recording we induced ventricular extrasystoles, and used long diastoles after premature contractions to adjust absolute pressure levels for the micromanometers. Data were recorded with the respirator off and were digitized at 200 samples per sec. In 4 of the dogs contrast was injected rapidly into the left atrium before and during LAD occlusion, and 2-D echocardiographic images were recorded immediately after the injection.

Calculations:

Pressure-derived variables:

We calculated LV peak systolic pressure, LV end-diastolic pressure and the time derivative (dP/dt) of LV pressure. The time course of the fall in LV pressure from peak negative dP/dt to 5 mmHg above end-diastolic pressure was characterized by the time constant (τ) of an assumed exponential decay to zero pressure (19). For definition of end-diastole and end-systole we used peak R of ECG and peak negative LV dP/dt, respectively. We calculated the time from end-diastole to the first diastolic crossover of LV and LA pressures (onset of transmitral filling). In 4 dogs we also calculated the difference between LV apical and LV outflow tract pressures.

Sonomicrometry-derived variables:

We calculated the following variables:

Peak systolic shortening (%ΔL) as:

\[
\frac{[(\text{end-diastolic length} - \text{minimal segment length})/(\text{end-diastolic length})]}{\text{end-diastolic length}} \times 100.
\]

Systolic lengthening (ischemic segments), (%ΔL) as:

\[
\frac{[(\text{end-diastolic length} - \text{peak systolic length of ischemic segment})/(\text{end-diastolic length})]}{\text{end-diastolic length}} \times 100.
\]
Post-systolic shortening (%ΔL) as:

\[ \frac{\text{end-systolic length} - \text{minimal segment length}}{\text{end-diastolic length}} \times 100. \]

During ischemia we calculated the time from onset of late systolic segmental shortening to peak early-diastolic LV apex to outflow tract pressure gradient.

The reported values represent the mean of three beats with the respirator off.

**Doppler-derived variables:**

Doppler measurements of shortening strains were represented by negative values and lengthening strains by positive values. However, in order to simplify comparison with sonomicrometry we report strain values in terms of percentage shortening:

Peak systolic shortening and lengthening were calculated in percentage of end-diastolic dimensions. Post-systolic shortening was calculated as segment shortening after end-systole, in percentage of end-diastolic dimension.

Flow velocities by 2-D color Doppler were recorded along the mitral-to-apical axis. We measured peak intraventricular velocities in the distal 1/3 of the left ventricle at the time of the first diastolic crossover of LV and LA pressures.

**Statistical analysis:**

Data are presented as mean ± SEM. Statistical analysis was performed with Student’s *t* test for paired data. For all statistical comparisons, *P* < 0.05 was considered significant.
Results

Hemodynamic variables before and during ischemia are presented in Table 1 and Figure 1. Peak systolic shortening by sonomicrometry and SDE decreased from 12.5 ± 2.4 to −12.5 ± 2.2 % (P<0.01) and 12.6 ± 1.7 to −9.5 ± 1.1 % (P<0.01), respectively, indicating dyskinesis.

Figure 2 demonstrates marked changes in intraventricular filling following LAD occlusion. During baseline the early-diastolic filling wave by 2-D color Doppler propagated rapidly towards the apex, as indicated by the uniformly red color throughout the LV cavity. During LAD occlusion, however, all experiments showed reversal of early-diastolic flow in the apex; i.e. the early-diastolic velocities were directed from the apex towards the base. The reversed apical velocities are represented by the blue colored area in Figure 2 (left lower panel). In order to quantify this change in filling we measured peak velocities in the distal 1/3 of the left ventricle at onset of transmitral filling, defined as the time of first diastolic crossover of LV and LA pressures. The peak velocity decreased from 9.2 ± 1.6 cm/s at baseline to −2.3 ± 0.4 cm/s (P<0.01) during LAD occlusion. The 2-D color pattern suggested that the transmitral filling wave propagated only a short distance into the left ventricle, and then was redirected towards the LV outflow tract where it appeared to rotate in a large vortex. These interpretations were confirmed by observations with echo contrast that was injected into the left atrium (Figure 2). Before ischemia the contrast propagated rapidly towards the apex and filled the entire LV cavity immediately after onset of transmitral filling. During LAD occlusion the contrast moved towards the mid-portion of the LV cavity and then rotated towards the LV outflow tract, while the apex remained free of contrast. Later in diastole the contrast moved towards the apex as part of a macro vortex.
The reversed apical flow during early LV filling was associated with post-systolic shortening of the ischemic apical segment (Figure 1B). Post-systolic shortening by sonomicrometry and SDE changed from 1.3 ± 0.4 and 0.8 ± 0.4 %, respectively, to 14.2 ± 2.4 (P<0.01) and 9.7 ± 1.7 % (P<0.01) during LAD occlusion. Figure 1 also demonstrates the temporal relationships between myocardial segmental motion and transmitral driving pressure. During LAD occlusion the ischemic segment was shortening at the time of LA and LV pressure crossover, and as demonstrated in Figure 3 the post-systolic shortening continued while the non-ischemic segment was lengthening. The ischemic segment continued to shorten 47 ± 8 and 65 ± 16 ms after onset of filling, by sonomicrometry and strain Doppler, respectively. The time constant of LV relaxation (tau) increased from 47 ± 4 to 64 ± 7 ms during ischemia (P<0.01).

Figure 4 displays the intraventricular pressure gradients as calculated between the apex and the LV outflow tract. During LV ejection the pressure gradient was directed from the apex towards the LV outflow tract, and there was a small reversal of the pressure gradient in late systole. The systolic pressure gradient decreased after LAD occlusion. During most of the isovolumic relaxation period (IVR) and during early transmitral filling the pressure gradient at baseline was directed towards the apex (peak value −1.1 ± 0.3 mmHg). During LAD occlusion, however, the gradient was reversed during most of the isovolumic relaxation period (peak value 1.2 ± 0.3 mmHg), consistent with the observed reversal of early-diastolic apical flow velocities. The time from onset of late systolic shortening of the ischemic segment by sonomicrometry to peak early diastolic apex-to-outflow tract pressure gradient was 25 ± 3 ms.
Discussion

Slowing of mitral-to-apical flow propagation has been observed in patients with acute myocardial ischemia in different clinical settings (13, 11), and has been reproduced in experimental models (13, 1, 12). The etiology of the impaired apical filling is unclear, but several mechanisms have been proposed (13, 12, 10, 14). In the present study we demonstrate that post-systolic shortening of ischemic myocardium has a profound effect on intraventricular flow. The post-systolic shortening resulted in early-diastolic ejection of blood from the apex towards the base, which resulted in markedly disturbed flow at the base of the ventricle, where flow from the apex encountered the transmitral filling wave. The post-systolic shortening was demonstrated by SDE and was confirmed by sonomicrometry. The present study therefore demonstrates the ability of Doppler echocardiography to quantify interactions between intraventricular flow and regional LV wall motion.

Stugaard et al. (13) reported delayed apical filling by color M-mode Doppler during LAD occlusion. In their study no early-diastolic apical flow was reported. This may be due to their velocity filter setting (12 cm/s) that was above the range of reversed apical velocities measured in the present study. The reversed velocities are very low, so the filter setting is critical in order to capture these velocities. Edvardsen et al. (2) reported reversed flow during the isovolumetric relaxation period in patients with anterior wall infarction. The velocity filter in that study was between 4 and 8 cm/s.
Mechanisms of delayed early-diastolic mitral-to-apical flow propagation:

Currently we have very limited insight into how LV intracavitary flow relates to myocardial properties. This is in part a consequence of the complex geometry of the ventricle and the continuous change in elastic properties of the myocardium throughout the cardiac cycle, which leads to very complex flow patterns. Furthermore, current imaging methods do not provide full visualization of the 3-D pattern that composes LV intracavitary flow. Nikolic et al. (6) have shown that regional deformation of the LV, even during IVR, lead to intraventricular pressure gradients and intraventricular flows. As demonstrated by Greenberg et al. (4) intraventricular pressure gradients can even be assessed by color Doppler echocardiography. In 2-dimensional models of non-ischemic ventricles it appears that the intraventricular flow field is represented by a number of vortices which expand in a circular fashion from the mitral tip region (20). However, during the early phase of filling, while transmitral flow is accelerating, the dominant flow vectors are directed towards the apex (7). This is demonstrated by the 2-D color flow image in Figure 2, which from an apical view shows uniformly red-encoded velocities throughout the ventricle. During this early phase of filling the propagation velocity of mitral-to-apical flow can be measured by color M-mode Doppler, and has been proposed as a measure of diastolic function (13, 1, 3, 4). Experimental data suggest that slowing of flow propagation is in part due to slowing of myocardial relaxation that leads to a decrease in the mitral-to-apical pressure gradient (12). It also appears that enhanced vortex formation in the diseased ventricle may contribute to slowing of flow propagation as measured by color M-mode Doppler (10). The present study clearly demonstrates that post-systolic shortening of apical myocardial segments may contribute to the impairment of
apical filling that is observed during acute ischemia. These different mechanisms are probably related.

As demonstrated by sonomicrometry the ejection of blood from the ischemic apical region started during isovolumic relaxation and persisted for some time after onset of transmitral filling. Therefore, lengthening of the non-ischemic segment (Figure 3) during early filling may be ascribed not only to transmitral flow, but also to redistribution of blood caused by post-systolic shortening. Blood that was ejected from the ischemic segment during early diastole encountered the transmitral jet, which was hindered from propagating towards the apex. As suggested by 2-D color flow and echo contrast the transmitral flow appeared to propagate only a short distance in the ventricle and then formed macro-vortices that rotated towards the LV outflow tract.

The observed reversal of the intraventricular pressure gradient during ischemia supported the interpretation that post-systolic shortening caused early-diastolic ejection of blood from the apical region. At baseline the pressure gradient during isovolumic relaxation and early filling was directed from the base towards the apex, and intraventricular flow velocities by color flow imaging were directed towards the apex. During LAD occlusion the pressure gradient during isovolumetric relaxation reversed and was directed towards the base, along with reversal of flow velocities. During ischemia there was a small time delay of about 25 ms between onset of late-systolic segmental shortening and peak apex-to-outflow tract pressure gradient, which is consistent with the notion that the gradient is caused by the segmental shortening.

Yellin et al. (20) described intraventricular vortices that occurred during LV filling due to shear between blood and mitral leaflet surface. The flow reversal described in the
The present study, however, started during isovolumic relaxation and therefore can not be attributed to a similar mechanism.

**Apical flow reversal – diagnostic implications:**

The mechanisms of post-systolic shortening were investigated by Skulstad et al. (9), and it was found that post-systolic shortening was a relatively nonspecific feature of ischemic myocardium. It could occur in severely ischemic myocardium by an entirely passive process, then representing passive recoil of dyskinetic segments. Post-systolic shortening also occurred in moderately ischemic myocardium, and was in part due to delayed active contraction, although passive components did contribute.

The present study suggests that color flow imaging may be helpful as an additional diagnostic tool for identifying regions with suspected post-systolic shortening. The finding of early-diastolic velocities that are directed from the apex towards the LV base is consistent with post-systolic shortening. Therefore, the two methods are complementary, and their combined use could increase the diagnostic power of echocardiography in the assessment of regional myocardial function. The clinical potential of this approach remains to be investigated.

**Limitations:**

The present animal model differs from a clinical setting in many regards, in particular due to the thoracotomy, the extensive instrumentation and the use of general anesthesia. However, the regional myocardial responses to coronary occlusion in terms of segmental
function should be relatively similar. Therefore, we believe the principle findings of this study may be valid for a clinical situation. This of course should be tested in a population with acute myocardial infarction.

One significant limitation of SDE is a strong angle dependency (18). In the present study with open chest we could easily optimise transducer position, and therefore minimised this problem. In a clinical setting, however, the problem of angle dependency of the echobeam relative to myocardial fiber orientation may be significant, in particular when studying apical segments.

The present study was limited to short-term ischemia. Potentially, with ischemia of longer duration, resulting in tissue necrosis and stiffening of the myocardium, one might see less passive systolic distension and subsequently less marked post-systolic shortening (5). This in turn may reduce the early-diastolic flow reversal.

**Conclusion:**

In the present experimental study we demonstrate that delayed early-diastolic LV apical filling during LAD occlusion may be due to post-systolic shortening of ischemic segments. During isovolumic relaxation and during the early phase of transmitral filling blood was ejected from the apical region and was redistributed towards basal portions of the cavity. This implies that in addition to global factors such as rate of LV relaxation and ventricular geometry, one should consider asynchronous wall motion, and in particular post-systolic shortening as a mechanism of disturbed intraventricular flow. Potentially, the use of color flow imaging along with SDE may represent a clinical tool for studying interactions between regional function and intraventricular flow. This combined imaging
might increase the diagnostic power of echocardiography in the assessment of myocardial function.
References


Legends to figures

**Figure 1A**: Baseline LV and left atrial (LA) pressures, the time derivative of LV pressure (LV dP/dt), myocardial longitudinal segment length and strain by Doppler in the LAD region and ECG. The first vertical line indicates the time of peak negative LV dP/dt, which was used as a marker of end-systole, and the second vertical line indicates the time of LV and LA crossover, which was used as a marker of onset of transmitral filling.

**Figure 1B**: Recordings obtained during LAD occlusion. Both sonomicrometry and strain by Doppler indicate systolic lengthening. Post-systolic shortening is demonstrated by both methods as shortening after the time of peak negative LV dP/dt (first vertical line). Note that post-systolic shortening continues after onset of transmitral filling (second vertical line).

**Figure 2**: **Upper panel**: Left ventricular early diastolic filling by 2-D color Doppler (left) and contrast echocardiography (right) from an apical view. At baseline the dominant flow wave propagated rapidly towards the apex as demonstrated by 2-D color Doppler (red-encoded velocities represents flow towards the apex) and by contrast echocardiography.

**Lower panel**: Left ventricular early diastolic flow by 2-D color Doppler (left) and contrast echocardiography (right). During LAD occlusion the 2-D color image recorded immediately after mitral valve opening, demonstrates a dramatic change of the flow pattern when compared to baseline. A counterflow coded blue, is directed towards the red-encoded
transmitral inflow. The echo-contrast propagates towards the mid-cavity, but does not reach the apex on this early diastolic frame.

**Figure 3**: LV and left atrial (LA) pressure tracings, the time derivative of LV pressure (LV dP/dt), segment lengths in the LAD- and Cx regions and ECG before and during LAD occlusion. Before ischemia both segments shorten during systole and lengthen during early diastole. During LAD occlusion, the ischemic segment lengthens during systole and shortens during early diastole. A indicates end-diastole, B indicates the time of peak negative LV dP/dt which was used as a marker of end-systole, C indicates first diastolic crossover of LV and LA pressures which was used as a marker of onset of transmitral filling.

**Figure 4A**: Recordings at baseline showing LV pressures measured at apex (PLVapex) and outflow tract (PLVoutflow tract), pressure difference between apex and left ventricular outflow tract, segment length in the LAD region and ECG. During most of systole the pressure gradient was positive (solid black area), which means it directed from the apex towards the outflow tract. During the isovolumetric relaxation period (IVR) and the initial phase of transmitral filling the pressure gradient was negative (hatched area), and was directed towards the apex.

**Figure 4B**: Recordings obtained during LAD occlusion. The ischemic segment lengthens during systole and shortens during IVR and during early transmitral filling. The intraventricular pressure gradient during IVR has reversed and is directed from the apex towards the LV outflow tract (solid black area).
A indicates end-diastole, B indicates peak negative LV dP/dt which was used as a marker of end-systole, C indicates first diastolic crossover of LV and LA pressures which was used as a marker of onset of transmitral filling.
Table 1. Hemodynamic parameters before and during LAD occlusion (mean ± SEM)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Ischemia</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, bpm</td>
<td>109 ± 5</td>
<td>109 ± 4</td>
<td>14</td>
</tr>
<tr>
<td>LV peak systolic pressure, mmHg</td>
<td>103 ± 4</td>
<td>86 ± 4*</td>
<td>14</td>
</tr>
<tr>
<td>LV end-diastolic pressure, mmHg</td>
<td>7.3 ± 0.7</td>
<td>8.7 ± 0.8</td>
<td>14</td>
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<tr>
<td>Peak LV intraventricular flow velocities early diastole, cm/s</td>
<td>9.2 ± 1.6</td>
<td>-2.3 ± 0.4*</td>
<td>10</td>
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<tr>
<td>End-diastolic segment length, LAD region, mm</td>
<td>8.3 ± 0.8</td>
<td>9.2 ± 1.0*</td>
<td>14</td>
</tr>
<tr>
<td>Peak systolic shortening LAD region by sonomicrometry, %</td>
<td>12.5 ± 2.4</td>
<td>-12.5 ± 2.2*</td>
<td>10</td>
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<td>Peak systolic shortening LAD region by strain Doppler echocardiography, %</td>
<td>12.6 ± 1.7</td>
<td>-9.5 ± 1.1*</td>
<td>10</td>
</tr>
<tr>
<td>Post-systolic shortening LAD region by sonomicrometry, %</td>
<td>1.3 ± 0.4</td>
<td>14.2 ± 2.4*</td>
<td>10</td>
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<tr>
<td>Post-systolic shortening LAD region by strain Doppler echocardiography, %</td>
<td>0.8 ± 0.4</td>
<td>9.7 ± 1.7*</td>
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<td>Time from end-diastole to first diastolic crossover of LV and LA pressures, ms</td>
<td>387 ± 18</td>
<td>405 ± 28</td>
<td>10</td>
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<tr>
<td>Tau, ms</td>
<td>47 ± 4</td>
<td>64 ± 7*</td>
<td>14</td>
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<tr>
<td>Peak pressure difference between LV apex and outflow tract during isovolumic relaxation, mmHg</td>
<td>−1.1 ± 0.3</td>
<td>1.2 ± 0.3 *</td>
<td>4</td>
</tr>
</tbody>
</table>

*P < 0.05 vs baseline
Figure 1A
Figure 1B

- LV pressure (mmHg)
- LV and LA pressures (mmHg)
- LV dP/dt (mmHg/s)
- Segment length LAD region (mm)
- Strain by Doppler (%)
- ECG

Ischemia
Figure 3