Cardiac diastolic dysfunction in conscious dogs with heart failure induced by chronic coronary microembolization

Robert M. Gill, Bonita D. Jones, Angela K. Corbly, Juan Wang, Julian C. Braz, George E. Sandusky, Jie Wang, and Weiqun Shen. Cardiac diastolic dysfunction in conscious dogs with heart failure induced by chronic coronary microembolization. Am J Physiol Heart Circ Physiol 291: H3154–H3158, 2006. First published July 28, 2006; doi:10.1152/ajpheart.00052.2006.—Left ventricular (LV) diastolic dysfunction is a fundamental impairment in congestive heart failure (CHF). This study examined LV diastolic function in the canine model of CHF induced by chronic coronary embolization (CCE). Dogs were implanted with coronary catheters (both left anterior descending and circumflex arteries) for CCE and instrumented for measurement of LV pressure and dimension. Heart failure was elicited by daily intracoronary injections of microspheres (1.2 million, 90- to 120-μm diameter) for 24 ± 4 days, resulting in significant depression of cardiac systolic function. After CCE, LV maximum negative change of pressure with time (dP/dtm) decreased by 25 ± 2% (P < 0.05) and LV isovolumic relaxation constant and duration increased by 19 ± 5% and 25 ± 6%, respectively (both P < 0.05), indicating an impairment of LV active relaxation, which was cardiac preload independent. LV passive viscoelastic properties were evaluated from the LV end-diastolic pressure (EDP)-volume (EDV) relationship (EDP = bo + kEDV) during brief inferior vena caval occlusion and acute volume loading, while the chamber stiffness coefficient (α) increased by 62 ± 10% (P < 0.05) and the stiffness constant (k) increased by 66 ± 13% after CCE. The regional myocardial diastolic stiffness in LV anterior and posterior walls was increased by 70 ± 25% and 63 ± 24% (both P < 0.05), respectively, after CCE, associated with marked fibrosis, increase in collagen I and III, and enhancement of plasminogen activator inhibitor-1 (PAI-1) protein expression. Thus along with depressed LV systolic function there is significant impairment of LV diastolic relaxation and increase in chamber stiffness, with development of myocardial fibrosis and activation of PAI-1, in the canine model of CHF induced by CCE.

MATERIALS AND METHODS

Animal preparation, measurements, and data analysis. This study was approved by the Lilly Institutional Animal Care and Use Committee; all animals were maintained in accordance with the National Institutes of Health Guide for Care and Use of Laboratory Animals (revised 1996). Male adult mongrel dogs weighting 20–25 kg (n = 19) were chronically instrumented for assessment of hemodynamics and cardiac function as previously described (5, 15). Both left anterior descending and left circumflex coronary arteries were isolated and implanted with custom-made silicon catheters for microembolization. Dogs were allowed to recover from surgery for 2–3 wk before experiments were begun.

Hemodynamic and LV systolic functional parameters included heart rate (HR), arterial pressure, left atrial pressure (LAP), LV pressure, change of pressure with time (dP/dt), LV internal dimension (LVID), LV stroke work, and minute work. Percent LV fractional shortening (%LVFS) was calculated as 100 × (LVEDD – LVESD)/LVEDD, where LVEDD and LVESD are end-diastolic and end-systolic dimensions.

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Address for reprint requests and other correspondence: W. Shen, Lilly Research Laboratories, Eli Lilly and Company, Indianapolis, IN 46285.

H3154 0363-6135/06 $8.00 Copyright © 2006 the American Physiological Society http://www.ajpheart.org
systolic LV dimensions, respectively. LV stroke work was measured as the integral area of LV pressure-dimension loops that were constructed from LV pressure and internal diameter obtained simultaneously. LV minute work was calculated as the product of LV stroke work and HR. Myocardial contractile parameters included wall thickening and end-systolic elastance (Ees). LV active relaxation indexes are LV maximum negative dP/dt, and isovolumic relaxation duration and time constant (\(\tau\)). LVEDV (ml) was calculated with an ellipsoidal model as

\[
LV_{EDV} = \frac{4}{3}\pi \times (EDD_{max} \times \frac{EDD_{max}}{2} \times EDWT) \times (EDD_{max} + EDD_{max} + EDWT),
\]

where EDD is end-diastolic dimension, and EDWT is end-diastolic wall thickness.

LV systolic parameters included LV systolic pressure, LV systolic dimension, LV fractional shortening, LV stroke work, LV minute work, and LV systolic pressure.

LV diastolic parameters included LV end-diastolic pressure, LV end-diastolic dimension, LV end-diastolic wall stress, LV relaxation, and LV isovolumic relaxation duration.

LV contractile and diastolic function in conscious dogs before and after chronic coronary microembolization.

Table 1. LV contractile and diastolic function in conscious dogs before and after chronic coronary microembolization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Heart Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV systolic pressure, mmHg</td>
<td>122±2</td>
<td>101±2*</td>
</tr>
<tr>
<td>LV dP/dt_{max}, mmHg/s</td>
<td>2.798±107</td>
<td>2.249±1.6*</td>
</tr>
<tr>
<td>LV fractional shortening, %</td>
<td>21.1±2.3</td>
<td>12.4±1.3*</td>
</tr>
<tr>
<td>LV stroke work, (\times 10^3) dyn/cm^2</td>
<td>125±11</td>
<td>56±9*</td>
</tr>
<tr>
<td>LV minute work, (\times 10^3) dyn/cm^2 min^(-1)</td>
<td>10.5±0.8</td>
<td>5.5±0.8*</td>
</tr>
</tbody>
</table>

Data are means ± SE for \(n = 13\) dogs. LV, left ventricular; dP/dt_{max}, maximum positive and negative change of pressure with time; \(\tau\), time constant. *\(p < 0.05\) vs. control.

LV end-diastolic pressure was calculated as

\[
LV_{EDP} = EDP_{VR} \times (EDD_{max}^2),
\]

where \(EDP_{VR}\) is LV end-diastolic pressure-volume relation. LV end-diastolic pressure-volume relation was assumed to be exponential and was estimated from the regional myocardial EDSSR in LV anterior and posterior walls, which was assumed to be exponential and was analyzed with curve fitting in the form \(\frac{LV_{EDP}}{EDP} = be^{\alpha EDV}\), where \(a\) is the myocardial stiffness coefficient (3, 9).

LV end-diastolic pressure, LV maximum negative dP/dt, and LV relaxation time constant \(\tau\) were calculated by curve fitting in the form \(\frac{LV_{EDP}}{EDP} = be^{\alpha EDV}\), where \(a\) is the myocardial stiffness coefficient (3, 9). Both LV EDPRV and EDSSR were constructed from the data collected from a brief inferior vena cava occlusion and an acute volume load.

Chronic coronary microembolization. CHF was induced by CCE with microspheres (Bangs Laboratories; 90- to 120-\(\mu\)m diameter) for 24 ± 4 days with an average of total 1.2 million microspheres, until LVEDP was \(\geq 18\) mmHg and LV maximum dP/dt (dP/dt_{max}) reduced by 20% of control value (5, 19).

Experimental protocols. To determine the impact of cardiac preload on LV isovolumic relaxation, five dogs were studied with a brief IVC occlusion that created a matching level of cardiac preload attained in the control state and heart failure. To determine LV chamber and regional myocardial stiffness, seven dogs were studied with both brief IVC occlusion and acute volume loading, in which 1,000 ml of saline was infused rapidly (\(\sim 100\) ml/min) under 250–300 mmHg of pressure with a pressure bag.

LV contractile and diastolic function in control and congestive heart failure (CHF) were examined under matching LV end-diastolic pressure (LVEDP) and heart rate (HR) during a brief inferior vena caval (IVC) occlusion. There was a significant decrease in LV minimum change of pressure with time (dP/dt_{min}), increase in LV relaxation time constant \(\tau\) and isovolumic relaxation duration, and decrease in LV maximum change of pressure with time (dP/dt_{max}) in CHF when LVEDP and HR were similar. *\(p < 0.05\), control vs. CHF.
Western blot analysis. The methods for Western blot analysis were described previously (15). Protein was extracted from LV myocardial biopsy specimens. Collagen I and III and PAI-1 were detected by monoclonal antibodies, and bands were quantified by densitometry. Calsequestrin was used as the internal control.

Statistical analysis. For all hemodynamic and cardiac functional data, values are expressed as means ± SE. The difference between the studied dogs before and after chronic coronary microembolization was determined by Student’s t-test for paired comparison. All changes were considered significant when \( P < 0.05 \) with a two-tailed t-distribution.

RESULTS

Systemic hemodynamics and LV contractile function. Compared with the control, CCE reduced mean arterial pressure from 96 ± 2 to 82 ± 2 mmHg (\( P < 0.05 \)) and increased HR from 86 ± 3 to 100 ± 5 beats/min (\( P < 0.05 \)), accompanied by elevation of mean LAP from 3 ± 1 to 13 ± 1 mmHg (\( P < 0.05 \)). Furthermore, CCE decreased LV systolic pressure by 26 ± 3 mmHg and depressed LV dP/dt\(_{max}\) by 18 ± 4%, LV fractional shortening by 39 ± 5%, LV stroke work by 53 ± 7%, and minute work by 47 ± 7% (all \( P < 0.05 \)) (Table 1).

Local myocardial contractile function was examined with LV anterior and posterior wall crystals. CCE reduced LV anterior wall thickening and \( E_a \) by 19 ± 11% and 11 ± 3% (\( P < 0.05 \)) respectively, and reduced LV posterior wall thickening and \( E_a \) by 64 ± 13% and 17 ± 3% (both \( P < 0.05 \)), respectively.

LV diastolic function. LVEDD and LV dP/dt\(_{min}\) were significantly increased after CCE, accompanied by an elevation of LV end-diastolic wall stress (Table 1). Furthermore, LV dp/dt\(_{min}\) decreased by 25 ± 2% (\( P < 0.05 \)) and LV isovolumic relaxation \( \tau \) and duration increased by 19 ± 5% and 25 ± 6%, respectively (both \( P < 0.05 \)), compared with their control values.

LV diastolic function with matched loading conditions. The impact of preload on LV isovolumic relaxation in heart failure was assessed in five dogs before and after CCE under a matched cardiac preload with a brief IVC occlusion. Figure 1 shows that, with similar LVEDP (3.6 ± 1.1 vs. 4.2 ± 1.2 vs. mmHg) and HR (101 ± 5 vs. 91 ± 7 beats/min), compared with the control LV dp/dt\(_{min}\) remained lower by 27 ± 6% (\( P < 0.05 \)) and both LV isovolumic relaxation \( \tau \) and duration remained higher by 53 ± 16% and 27 ± 6%, respectively (both \( P < 0.05 \)), after CCE. Thus the impairment of LV isovolumic relaxation after CCE was preload independent.

LV chamber stiffness. Figure 2A illustrates a representative LV EDPVR in an individual dog studied before and after CCE. Before embolization, the increase in LVEDP was small despite a relative large increase in LV EDPVR, and this relationship became steeper only when LVEDP was >10 mmHg. After CCE, LV EDPVR was not only significantly shifted to the right, indicating a great enlargement of the LV chamber, but also became much steeper, with an increase in LV chamber stiffness coefficient \( \alpha \) by 62 ± 10% (\( P < 0.05 \)) (Table 2), suggesting a marked reduction of chamber compliance. Figure 2B further demonstrates a representative LV chamber stiffness (dP/dV) and LVEDP relationship. LV chamber stiffness increased linearly with LVEDP and chamber stiffness constant \( k \), where the slope of this relationship was significantly increased by 66 ± 13% after CCE (Table 2). Together, our results suggest a significant increase in LV chamber stiffness in CHF induced by CCE.

Myocardial diastolic stiffness. Myocardial diastolic stiffness was evaluated by a regional myocardial EDSSR in LV anterior and posterior walls. Figure 3 demonstrates a representative change in myocardial diastolic stiffness in an individual dog studied before and after CCE. In the control, the regional myocardial end-diastolic stress was only slightly elevated despite a large increase in regional myocardial end-diastolic strain during an increase in LV chamber volume. After CCE, this curve became much steeper, indicating a greater elevation of regional myocardial end-diastolic stress in response to an increase in regional myocardial end-diastolic strain. The summarized data (Table 2) from seven dogs showed that the regional myocardial stiffness was increased by 70 ± 25% in the LV anterior wall and by 63 ± 24% in the LV posterior wall (both \( P < 0.05 \)) after CCE.

Myocardial fibrosis and increased PAI-1 protein expression. Western blot analysis showed significant increases in myocardial collagen I and III by 2- and 10-fold (both \( P < 0.05 \)), respectively. Collagen I and III demonstrated a significant elevation after CCE.

Table 2. LV myocardial and chamber stiffness in conscious dogs before and after chronic coronary embolization

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Heart Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior wall stiffness coefficient (( n = 6 ))</td>
<td>17.5 ± 1.4</td>
<td>31.1 ± 6.7*</td>
</tr>
<tr>
<td>( \alpha ), mm⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior wall stiffness coefficient (( n = 7 ))</td>
<td>18.4 ± 1.6</td>
<td>31.3 ± 6.1*</td>
</tr>
<tr>
<td>( \alpha ), mm⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamber stiffness coefficient (( n = 7 ))</td>
<td>0.11 ± 0.02</td>
<td>0.17 ± 0.04*</td>
</tr>
<tr>
<td>( b ), mmHg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamber stiffness constant (( n = 7 ))</td>
<td>0.04 ± 0.01</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>( k ), mm⁻¹</td>
<td>0.09 ± 0.01</td>
<td>0.14 ± 0.02*</td>
</tr>
</tbody>
</table>

Values are means ± SE for \( n \) dogs. \( b \), intercept value. *\( P < 0.05 \) vs. control.
respectively, and a significant increase in myocardial PAI-1 level by ~2.3-fold ($P < 0.05$) in the failing heart with CCE (Fig. 4) compared with normal hearts.

**DISCUSSION**

CCE resulted in significant LV diastolic functional abnormalities that covered both active and passive aspects of diastolic function, with a depressed LV systolic function. Importantly, the impairment of LV isovolumic relaxation after CCE was independent of the alteration of the cardiac preloading condition, and increases in LV chamber and regional myocardial diastolic stiffness were accompanied by development of tissue fibrosis and activation of PAI-1 after myocardial injury.

Ventricular isovolumic relaxation is an active diastolic process resulting from the sequestration of calcium and cross bridge uncoupling and can be quantified by measurements of LV dP/d$t_{min}$ and isovolumic relaxation $\tau$ and duration (3, 8, 9). In an earlier investigation of the canine pacing CHF model, Komamura et al. (8) showed that impaired LV isovolumic relaxation in CHF was associated with increased cardiac preloading condition and could be reversed by normalization of the loading condition on the heart. In the present study, we found that, with the significant impairment of LV isovolumic relaxation by CCE, LV dP/d$t_{min}$ remained lower and LV isovolumic relaxation duration and relaxation $\tau$ remained longer even under the condition of reduced cardiac preload during a brief IVC occlusion (Fig. 1). Thus our results suggest that, different from the canine pacing model of CHF, the abnormalities of active diastolic relaxation in CHF following myocardial injury were load independent and therefore could not be reversed by normalization of the loading condition.

Abnormality in ventricular passive diastolic properties (the component determined by the distensibility of the myocardium) is one of the fundamental aspects responsible for the hemodynamic and symptomatic abnormalities of heart failure (7, 13, 20). LV passive diastolic properties could be well demonstrated by EDPVR (2). It is important to recognize that EDPVR of the LV chamber in the intact heart is nonlinear, the curve is flat in the low pressure-volume range, and the curve rises sharply as the ventricle becomes distended (3, 8, 16). The EDPVR constructed from nonlinear curve fitting may appear very different if the chamber volume data are collected from different end-diastolic pressure ranges (as commonly occurs when comparing a normal state to a heart failure state), although the data may delineate an identical EDPVR in the overlapping pressure-volume ranges. Therefore, it becomes critical to cover both low and high pressure-volume ranges in constructing the entire EDPVR. In the present study, using the combination of brief IVC occlusion and acute volume loading to dramatically change LV chamber volume, we constructed...
both low and high parts of the EDPVR and demonstrated a right upward shifting in the EDPVR after CCE (Fig. 2A). In contrast to the nonlinear relationship of EDPVR, the relationship of dP/dV and LVEDP is linear, and the slope of this relationship, termed the chamber stiffness constant, has been used by many investigators as an index of LV diastolic chamber properties (3, 9). In the present study, we showed a significant increase in the slope of the LV dP/dV and LVEDP relationship by 66 ± 13% after CCE (Fig. 2B). Altogether, our analysis clearly demonstrated a significant increase in LV chamber stiffness in the canine model of CHF induced by CCE.

Passive myocardial properties greatly impact the chamber stiffness and can be characterized by myocardial EDSSR (3, 9). Analogous to the EDPVR, this relationship is nonlinear. In the present study, the myocardial diastolic stiffness was estimated from myocardial regional EDSSRs in LV anterior and posterior walls before and after CCE. The significant shifting of myocardial EDSSRs following CCE indicates an increased myocardial diastolic stiffness, which could contribute to the change in LV chamber stiffness in CHF.

Alteration of the extracellular matrix is a major mechanism contributing to the change of myocardial and chamber passive diastolic properties (4, 7, 13, 20). As consequence of the myocardial injury following CCE, our histological examination revealed an interstitial and perivascular fibrosis (5), associated with an accumulation of collagen I and III, consistent with these earlier reports (10, 13, 17). Furthermore, we showed an increase in the protein expression of PAI-1, the principal inhibitor of plasminogen activation. PAI-1 could promote fibrosis by preventing the activation of matrix metalloproteinases, enzymes that degrade collagenous proteins, and the degradation of extracellular matrix by plasminogen activators and plasmin (1, 18). Thus the significant development of myocardial fibrosis, related to the activation of PAI-1, could be an important underlying molecular alteration contributing to the impairment of myocardial passive diastolic properties.


