Angiotensin II Type 2 Receptor Overexpression Preserves Left Ventricular Function After Myocardial Infarction

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Background—The role of the angiotensin II type 2 receptor (AT$_2$-R) in left ventricular (LV) remodeling may depend on the underlying stimulus. We hypothesized that cardiac AT$_2$-R overexpression in transgenic (TG) mice would attenuate remodeling after myocardial infarction (MI).

Methods and Results—Ten wild-type (WT) C57BL/6 mice and 12 TG mice that overexpress the AT$_2$-R in the heart were studied by cardiac MRI at baseline and days 1, 7, and 28 post-MI induced by 1 hour of occlusion of the LAD followed by reperfusion. Short-axis images from apex to base were used to determine LV mass index, end-diastolic and end-systolic volume indices (EDVI, ESVI), regional wall thickness and thickening, and ejection fraction (EF). Gadolinium-DTPA was infused 20 minutes before day 1 imaging to assess infarct size. At baseline, heart rate, blood pressure, LV mass index, and EDVI were similar between groups. Baseline ESVI was lower (0.20±0.07 versus 0.45±0.15 μL/g, P<0.001) and EF higher (82.3±4.9% versus 67.7±5.3%, P<0.001) in TG than WT. Infarct size was similar (36.6±7.2% in WT, 34.0±7.8% in TG, P=NS). When controlled for baseline differences, ESVI was significantly less and EF significantly higher at all time points in TG versus WT. At day 28, ESVI was 1.05±0.32 μL/g in TG and 1.63±0.41 μL/g in WT, P<0.03, and EF was 47.3±5.8% versus 34.1±9.2%, P<0.003, respectively. Regional wall thickness and thickening were greater in TG both at baseline and at day 28. At day 28, blood pressure and LV dP/dt were higher in TG.

Conclusions—Cardiac AT$_2$-R overexpression improves LV systolic function at baseline and preserves function during post-MI remodeling. (Circulation. 2002;106:106-111.)

Key Words: remodeling ■ myocardial infarction ■ magnetic resonance imaging ■ angiotensin ■ receptors

Left ventricular (LV) remodeling is common after large, especially anterior myocardial infarction (MI).1-3 LV end-systolic volume (ESV) is the most powerful predictor of mortality after MI.4 Remodeling is associated with elongation of noninfarcted myocardial segments5,6 and cellular hypertrophy.7,8 Hypertrophy in noninfarcted myocytes is in part initiated by wall stress, local stretch, and activation of the local renin-angiotensin system, resulting in increased levels of angiotensin II (Ang II).9-11 Cardiovascular effects of Ang II include vasoconstriction, cellular hypertrophy, and interstitial fibrosis.

Most of the known physiological effects of Ang II are mediated through the angiotensin II type 1 receptor (AT$_1$-R), whereas the physiological functions of the angiotensin II type 2 receptor (AT$_2$-R) are less well understood. The AT$_2$-R induces vasoconstriction, aldosterone secretion, cellular growth, and catecholamine release,11 promoting hypertrophy and remodeling. Conversely, the AT$_2$-R inhibits growth and remodeling, induces vasodilation,12 and appears to be expressed at low levels in normal cardiac myocytes13 and upregulated in pathological states.11,14,15 Conflicting data regarding its antigrowth effects have emerged from studies of mice lacking the AT$_2$-R in models of pressure-overload hypertrophy.16,17

We hypothesized that AT$_2$-R cardiac overexpression would attenuate remodeling in the intact post-MI heart. Cardiac MRI is an excellent method for assessing cardiac structure and global function in both infarcted and transgenic (TG) mice.18 To test this hypothesis, we used cardiac MRI to image LV size and global function serially after reperfused MI in a TG mouse that overexpresses the AT$_2$-R and in wild-type (WT) controls.

Methods

Mouse Model

Animal protocols were performed in accordance with the Guide for the Care and Use of Laboratory Animals (NIH publication No. 85–23, revised 1996). They were approved by the Institutional Animal Care and Use Committee of the University of Virginia. Male C57BL/6 mice were obtained from Jackson Laboratories (Bar Harbor, Maine) and housed in a temperature-controlled environment with a 12-hour light/dark cycle. Mice were maintained on a standard mouse chow diet (LabDiet 5008, PMI Nutrition International, Inc., St. Louis, Missouri) and had free access to water.

Antilreeze, a commercially available preparation of unmodified human IgG containing monomeric IgG, was obtained from Alpha-Tech (Silver Spring, Maryland). Antilazeera was used to coat the inner surface of the aorta, the left ventricular chamber, and the coronary sinus for 2 hours. Antilazeera was then washed out, and the heart was reperfused. In the absence of antilazeera, the aorta is not patent, the left ventricular chamber is not filled, and the coronary sinus is not patent. We used antilazeera to prevent post-MI remodeling. We used antilazeera to prove that post-MI remodeling is present in the absence of antilazeera.

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60 minutes by tying down silk suture over a short length of PE-20

mice 10 to 14 weeks old at the start of the study were studied before

primers.

confirmed with sense and antisense polymerase chain reaction

of RNA from the mouse tail. The presence of the transgene was

single-cell fertilized mouse embryos to generate TG mice (C57BL/6

DNA fragment, which was then microinjected into the pronuclei of

was recorded by a MacLab recording system.

Figure 1. A, End-systolic short-axis Gd-enhanced cine MR images at day 1 post-MI in WT control (left) and TG mice (right). Note similar hyperenhanced infarct area in both mice. Also note increased end-systolic cavity area in WT mouse compared with TG mouse despite similar infarct sizes. B, End-systolic short-axis cine MR images without Gd at day 28 post-MI in WT control (left) and TG mice (right). Note marked anteroseptal thinning and markedly increased end-systolic cavity in WT mouse compared with the TG mouse.

85-23, revised 1996) and were approved by the University of Virginia Animal Care and Use Committee. The TG mouse strain with cardiac overexpression of the AT₂R was developed in the laboratory of H. Matsubara, MD (Kansai Medical University, Osaka, Japan). The mouse α-myosin heavy chain promoter (MHC)²⁰ and a mouse AT₂R cDNA²¹ were subcloned into pBluescript(−) plasmid.²⁰ The recombinant plasmid pMHC-AT₂R was digested to an 8.6-kb DNA fragment, which was then microinjected into the pronuclei of single-cell fertilized mouse embryos to generate TG mice (C57BL/6 strain). Transgene expression was assessed by Northern blot analysis of RNA from the mouse tail. The presence of the transgene was confirmed with sense and antisense polymerase chain reaction primers.

Twelve male TG mice and 10 age-matched male WT C57BL/6 mice 10 to 14 weeks old at the start of the study were studied before and serially after MI over a period of 28 days.

Surgery

Surgical procedures for infarct creation and reperfusion were the same as reported previously.²² The coronary artery was occluded for 60 minutes by tying down silk suture over a short length of PE-20 tubing. Successful occlusion was verified by color change of the LV distal to the ligation site and expected ECG changes. After 60 minutes, reperfusion was achieved by cutting the suture.

Magnetic Resonance Imaging

Mice were heavily sedated with 10 to 15 mg/kg diazepam and imaged at baseline before MI (day 0) and at days 1 (Figure 1A), 7, and 28 (Figure 1B) post-MI. Imaging was performed on a Varian 200/400 Inova 4.7-T MRI system with Magnex gradients (80 G/cm maximum strength) and a custom-built 2.5-cm birdcage receiver coil (RF Design Consulting). Before imaging on day 1 post-MI studies, 0.3 mmol/L per kg Gd-DTPA was infused intraperitoneally 20 minutes before imaging. The ECG signal was amplified (CP-302, Sable Systems), and a trigger pulse was generated from the QRS complex (Tachometer CFT-1D, Sable Systems). A 2D fast, low-angle shot (FLASH) sequence was used to obtain orthogonal long-axis images. For simultaneous assessment of LV size, global and regional LV function, and infarct size (the latter only on day 1 imaging), short-axis cine MRI was performed with an ECG-triggered 2D cine FLASH sequence (Figure 1). Short-axis slices were planned from the second orthogonal long-axis image. The echo time was 3.9 ms, and the TR value was adjusted continuously (8.0 to 14.0 ms) to obtain 16 equally spaced phases during each cardiac cycle. A 20° flip angle was used except for the post-Gd-DTPA images. For the contrast-enhanced images, a 60° flip angle was used to increase the amount of T1 weighting. A 2.56×2.56-cm field of view was acquired with a matrix of 128×128 zero-filled to 256×256, yielding a final resolution of 100×100×1000 μm³. Three signal averages were used, resulting in an acquisition time for each slice of ~4 minutes. Six to 8 short-axis slices 1 mm thick were obtained to cover the entire heart, resulting in a total scan time of 30 to 45 minutes for each mouse.

Hemodynamic Studies

Noninvasive tail-cuff blood pressures were measured at baseline in the conscious state in 12 TG and 6 WT mice with a Visitech BP-2000 system. Invasive measurement of blood pressure and LV filling pressures and function was performed on all mice after the day 28 post-MI MRI. For the latter studies, mice were anesthetized with an intraperitoneal injection of pentobarbital sodium 50 μg/g body wt, enhanced by local subcutaneous injection of 0.5% bupivacaine 100 μL. The right common carotid artery was cannulated with a PE-10 tubing to measure peripheral arterial pressure. LV pressure was obtained by direct puncturing of the LV via the left 5th interspace with a 27-gauge needle connected to PE-50 tubing. Blood pressure and LV pressure as well as heart rate and developed pressure (dP/dt) were recorded by a MacLab recording system.

Image Analysis

Images were quantitatively analyzed by use of the ARGUS (Siemens Medical Systems) image analysis program. Endocardial contours were manually traced by a blinded image analyst at end diastole and end systole for each slice. The LV end-diastolic volume (EDV), ESV, stroke volume (SV), and ejection fraction (EF) were computed by use of Simpson’s rule. The epicardial border was similarly traced at end-diastole, and the endocardial area was subtracted and multiplied by myocardial density (1.05) for determination of LV mass (LVM). End-diastolic wall thickness and percent wall thickening at baseline and day 28 post-MI were calculated by use of ARGUS and a centerline method and averaged for apical, mid, and basal slices. ESV, EDV, SV, and LVM were indexed to body weight in grams (ESVI, EDVI, SVI, and LVMI).

The area of delayed hyperenhancement in day 1 post-Gd images (Figure 1A) was defined as the infarcted region as previously validated by TTC staining.²³ The hyperenhanced area, defined as the region with signal intensity >2 SD above the mean of the remote region, was planimetered by use of ARGUS and infarct area calculated as a percentage of total LVM.

Statistical Analysis

Changes from baseline in global parameters over time, including heart rate, LVM, EDVI, ESVI, and EF of the TG mice were compared with those of WT mice by repeated-measures ANCOVA, including baseline values as a covariant. LVM, ESVI, and EDVI were logarithmically transformed before analysis. Comparisons between groups and within groups between time points were adjusted with the Bonferroni correction for multiple comparisons. Between-group changes in wall thickness and thickening from day 0 to 28 post-MI were compared by 2-way ANOVA. Between-group differences in baseline global parameters, noninvasive and invasive hemodynamics, infarct size, and signal intensity ratios were compared by unpaired t test. All values are presented as mean ± SEM, with a value of P < 0.05 defined as significant.

Results

Baseline Hemodynamics

The mean blood pressure and heart rate in conscious animals at baseline measured by a noninvasive tail-cuff apparatus
were 104±9 mm Hg and 578±79 bpm in WT mice (n=6) and 111±11 mm Hg and 632±63 bpm in TG mice (n=12) (P=NS).

Baseline LV Size and Function
Body weight, LVMI, and EDVI were similar between groups at baseline (Table 1). TG mice demonstrated significantly smaller ESVI (0.20±0.07 versus 0.45±0.15, P<0.001) and higher EF (82.3±4.9% versus 76.7±5.3%, P<0.0001) than WT mice but no difference in SVI (Table 1). End-diastolic wall thickness was higher in TG than WT mice in the apex and mid-LV (Table 2), and wall thickening was higher in the base and mid-LV (Table 2).

Infarct Size
Signal intensity ratios for hyperenhanced to remote regions were similar between groups (3.83±1.39 versus 3.67±1.15, P=NS). Infarct size by contrast-enhanced MRI was similar in WT and TG mice, 36.6±7.2% and 34.0±7.8% of LVM, respectively (P=NS) (Figure 1A).

MRI Parameters of Post-MI Remodeling
Heart rates and body weights did not change during the study period in either group. In both groups, LV dysfunction on day 1 post-MI was characterized by an increase in ESVI and LVMI and a decrease in EF and SVI (Table 1). LV size and function were better preserved in TG mice than in WT mice.

### TABLE 1. Global Cardiac Parameters by MRI

<table>
<thead>
<tr>
<th>Strain</th>
<th>Baseline</th>
<th>Day 1</th>
<th>Day 7</th>
<th>Day 28</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWT, g</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>27.8±1.2</td>
<td>25.6±1.9†</td>
<td>27.0±1.5†</td>
<td>28.2±1.3‡§</td>
</tr>
<tr>
<td>TG</td>
<td>27.3±2.3</td>
<td>25.5±2.2†</td>
<td>27.6±1.9†</td>
<td>28.0±1.8‡</td>
</tr>
<tr>
<td>HR bpm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>383±52</td>
<td>401±77</td>
<td>442±114</td>
<td>406±76</td>
</tr>
<tr>
<td>TG</td>
<td>431±103</td>
<td>457±43</td>
<td>425±92</td>
<td>392±92</td>
</tr>
<tr>
<td>LVMI mg/g</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>2.82±0.36</td>
<td>3.44±0.32†</td>
<td>3.50±0.47†</td>
<td>3.65±0.49†</td>
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<tr>
<td>TG</td>
<td>2.98±0.28</td>
<td>3.70±0.40†</td>
<td>3.26±0.30‡</td>
<td>3.42±0.50‡</td>
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<tr>
<td>ESVI µL/g</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>1.38±0.34</td>
<td>1.58±0.18†</td>
<td>2.31±0.45†</td>
<td>2.54±0.61†‡</td>
</tr>
<tr>
<td>TG</td>
<td>1.15±0.17</td>
<td>1.16±0.16*</td>
<td>1.32±0.40*</td>
<td>1.99±0.50†‡§</td>
</tr>
<tr>
<td>EDVI µL/g</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>0.45±0.15</td>
<td>0.85±0.23†</td>
<td>1.33±0.32†</td>
<td>1.63±0.41†‡</td>
</tr>
<tr>
<td>TG</td>
<td>0.20±0.07*</td>
<td>0.41±0.10*†</td>
<td>0.59±0.32†</td>
<td>1.05±0.32†‡§</td>
</tr>
<tr>
<td>SVI µL/g</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>0.93±0.22</td>
<td>0.73±0.18†</td>
<td>0.98±0.24</td>
<td>0.85±0.25</td>
</tr>
<tr>
<td>TG</td>
<td>0.94±0.13</td>
<td>0.75±0.12†</td>
<td>0.74±0.13†</td>
<td>0.93±0.50</td>
</tr>
<tr>
<td>EF %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>67.7±5.3</td>
<td>46.6±10.6†</td>
<td>42.7±6.7†</td>
<td>34.1±9.2†</td>
</tr>
<tr>
<td>TG</td>
<td>82.3±4.9*</td>
<td>64.7±6.3*†</td>
<td>58.5±13.6*†</td>
<td>47.3±5.8*‡§</td>
</tr>
</tbody>
</table>

TG mice were compared to WT using repeated measures ANCOVA adjusted for baseline differences.

BWT indicates body weight.
*P<0.05 versus WT. Within group: †P<0.05 vs baseline; ‡P<0.05 vs day 1; §P<0.05 vs day 7.

### TABLE 2. End-Diastolic Wall Thickness and End-Systolic Wall Thickening at Baseline and Day 28 Post-MI

<table>
<thead>
<tr>
<th>End-Diastolic Wall Thickness, mm</th>
<th>Wall Thickening, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Mid</td>
</tr>
<tr>
<td>WT</td>
<td>0.95±0.17</td>
</tr>
<tr>
<td>TG</td>
<td>0.97±0.46</td>
</tr>
<tr>
<td>Day 28</td>
<td>0.88±0.09</td>
</tr>
<tr>
<td>TG</td>
<td>0.97±0.09*</td>
</tr>
</tbody>
</table>

*P<0.05 vs WT; †P<0.001 vs baseline.
as evidenced by lower EDVI (1.16±0.16 versus 1.58±0.18 μL/g, P<0.001) and ESVI (0.41±0.10 versus 0.85±0.23 μL/g, P<0.001) and higher EF (64.7±6.3% versus 46.6±10.6%, P<0.002) (Table 1, Figures 2, 3, and 4). No significant changes in LV size or function occurred in either group between days 1 and 7 post-MI, other than a decrease in LVMI in TG from 3.70±0.40 to 3.26±0.30 mg/g (P<0.05).

By day 28 post-MI, there was a stepwise increase in EDVI and ESVI and a decrease in EF in both groups (Table 1). When corrected for baseline differences, however, ESVI was lower and EF was higher at each time point in TG mice (Figure 2, 3, and 4). At day 28, ESVI was 1.05±0.32 μL/g in TG and 1.63±0.41 μL/g in WT, P<0.03, and EF was 47.3±5.8% versus 34.1±9.2%, P=0.002, respectively.

LVMI was similar between groups at each time point (Table 1), and SVI transiently decreased in both groups at day 1 but returned to baseline values by day 28.

**Regional LV Function After MI**

At day 28 post-MI, end-diastolic wall thickness was greater at the base and apex in TG mice than in WT controls (Table 2) and tended to be higher in the midventricle (Figure 1B). Systolic wall thickening remained greater in TG than WT in both the base and midventricle (Table 2).

**Hemodynamics at 28 Days After MI**

There was no difference in heart rates between the baseline and post-MI follow-up or between the 2 groups. Systolic, diastolic, and mean blood pressures were greater in TG than WT (Table 3). LV end-diastolic pressure was lower in TG than WT mice (4.1±0.7 versus 7.5±0.8 mm Hg, P<0.01). LV systolic and diastolic function was preserved in TG mice compared with WT (Table 3).

**Discussion**

This study demonstrates 2 important findings: (1) AT2 overexpression in the murine heart is associated with improved LV function at baseline, and (2) during LV remodeling after reperfused MI, LV global and regional function are preserved in this TG model. At baseline, TG mice had smaller ESVI and increased regional and global function compared with WT controls, whereas LVMI and SVI were similar. During LV remodeling after reperfused MI, ESVI remained lower and EF higher at each time point up to day 28 post-MI. At day 28,
LV wall thickness, filling pressures, and contractile function measured invasively and noninvasively were higher in TG than WT mice. The beneficial effects of AT\textsubscript{1} overexpression on LV remodeling and LV function occurred in the absence of any differences in heart rate, SV, or LVM between the 2 groups. These results indicate a beneficial role for the AT\textsubscript{2} in volume-overload states, including post-MI remodeling.

The mechanism of increased systolic function at baseline with AT\textsubscript{1} overexpression is unclear. No developmental abnormalities or cardiac morphological or histological differences have been observed in mice lacking the AT\textsubscript{2} gene.\textsuperscript{4,25} No differences were noted in cardiac morphology or ratio of heart to body weight between WT and cardiac AT\textsubscript{2}–overexpressed mice,\textsuperscript{19} but no in vivo measures of cardiac function were made. In an isolated heart preparation, dP/dt was similar to that in WT.\textsuperscript{19} The hypertensive and chronotropic response to Ang II, however, was markedly attenuated.\textsuperscript{19} It may be that attenuation of effects of basal Ang II levels enhances systolic function. Another potential mechanism is altered geometry and lower regional wall stress, because wall thickness is greater in TG mice with similar end-diastolic volume. Another potential mechanism is vaso-dilation, a known effect of AT\textsubscript{2}–overexpression in vascular smooth muscle.\textsuperscript{26} In the present model, however, AT\textsubscript{1} overexpression is limited to the myocardium, and blood pressure was similar at baseline between strains.

The protective effect of AT\textsubscript{2}–overexpression on LV systolic function post-MI is consistent with previous work suggesting that the AT\textsubscript{2} limits growth and fibrosis. In addition, the reduction in wall stress with greater wall thickness and smaller cavity volumes probably contributes to the attenuation of post-MI remodeling. The AT\textsubscript{2}–is upregu-lated in pathological states associated with tissue remodeling or inflammation, such as cardiac hypertrophy, aortic banding models, MI models, and cardiomyopathy. In failing cardio-myopathic hamster hearts, the AT\textsubscript{2}–is upregulated and reexpressed by cardiac fibroblasts,\textsuperscript{11} which inhibits the progression of interstitial fibrosis. One week after MI in a rat model, a 2- to 3-fold increase in AT\textsubscript{2} mRNA was demon-strated in noninfarcted and infarcted regions.\textsuperscript{15} In a similar model, blockade of the AT\textsubscript{2}–negatively affected cardiac output and SV.\textsuperscript{27}

In pressure-overload models, the counterregulatory hypothesis of the AT\textsubscript{2}–remains controversial.\textsuperscript{28} In a rat model of ascending aortic banding, AT\textsubscript{1}–blockade allowed cardiac hypertrophy to continue unabated in response to Ang II.\textsuperscript{29} Two other studies, however, demonstrate that in AT\textsubscript{1}–null mice, LVH in response to pressure overload was prevented.\textsuperscript{16,17} Studies in AT\textsubscript{1}–null mice may not be representative in that levels are low in normal hearts and are upregulated only in disease.\textsuperscript{13}

Mechanisms underlying the benefit of AT\textsubscript{2}–overexpression may involve both bradykinin and nitric oxide. Mice with AT\textsubscript{2}–overexpression in vascular smooth muscle\textsuperscript{26} demonstrate AT\textsubscript{2}–mediated blockade of the Na\textsuperscript{+}/H\textsuperscript{+} exchanger, causing intracellular acidosis, which increases kininogenase activity and bradykinin production. The pressor effect of Ang II was abolished but was reinstated by either bradykinin subtype 2 receptor blockade (icatibant) or nitric oxide synthase inhibition.

Recent evidence suggests that the AT\textsubscript{2}–underlies the cardioprotective effects of AT\textsubscript{1}–antagonism. In rats treated with AT\textsubscript{1}–antagonists for 2 months post-MI, the beneficial effects were blocked by AT\textsubscript{2}–antagonism and partially blocked by icatibant.\textsuperscript{30} The benefits of AT\textsubscript{1}–antagonists may therefore be partly a result of activation of the AT\textsubscript{2}–, mediated in turn by bradykinin. A previous study by our group in an ovine infarction model showed that combination therapy with ACE inhibition and AT\textsubscript{1}–antagonism was associated with an increase in the ratio of AT\textsubscript{2}–/AT\textsubscript{1}–,\textsuperscript{31} and this combination attenuated LV remodeling to a greater extent than standard doses of either therapy alone.\textsuperscript{32} This suggests that modulation of the AT\textsubscript{2}–may mediate much of the benefit of renin-angiotensin system blockade post-MI.

**Study Limitations**

Baseline differences between groups complicate the analysis of changes post-MI. The statistical analysis performed, however, accounted for baseline differences. The study was extended only to 28 days post-MI. Studies extended to a later time point might have demonstrated different results. Previous studies by our group, however, demonstrate that most of the changes in ESVI and EF that take place over 6 months post-MI in the mouse model occur by day 28 post-MI.\textsuperscript{33} Further work is necessary to understand the effects of AT\textsubscript{2}–overexpression on interstitial fibrosis and hypertrophy at the myocyte level. With the further development of MRI tagging techniques for murine imaging, the analysis of regional myocardial function in this post-MI model will become more refined.

**Acknowledgments**

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**References**


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