Nitric Oxide Mediates Benefits of Angiotensin II Type 2 Receptor Overexpression During Post-Infarct Remodeling

Christina M. Bove, Zequan Yang, Wesley D. Gilson, Frederick H. Epstein, Brent A. French, Stuart S. Berr, Sanford P. Bishop, Hiroaki Matsubara, Robert M. Carey, Christopher M. Kramer

Abstract—We hypothesized that nitric oxide (NO) mediates the benefits of cardiac angiotensin II type 2 (AT2-R) overexpression during postmyocardial infarction (post-MI) remodeling. Eleven wild-type (WT) C57BL/6 mice and 28 transgenic (TG) mice with AT2-R overexpression were studied by cardiac magnetic resonance imaging (CMR) at baseline and days 1 and 28 post-MI induced by left anterior descending artery occlusion and reperfusion. Sixteen TG mice were treated from day 1 through 28 post-MI with the NO synthase inhibitor L-NAME (TG-Rx). Left ventricular mass index (LVMI), end-diastolic volume index (EDVI) and end-systolic volume index (ESVI), wall thickness, percent thickening, and ejection fraction (EF) were measured. Infarct size on day 1 was assessed by post-contrast CMR. Interstitial collagen was quantified in noninfarcted regions. At baseline, heart rate (HR), blood pressure (BP), LVMI, EDVI, and ESVI were similar between groups, as were infarct size and weekly post-MI HR and systolic BP. By day 28 post-MI, EDVI and ESVI were similar in WT and TG-Rx, but significantly lower in TG (ESVI: 1.41±0.18 μL/g versus 2.53±0.14 μL/g in WT; 2.17±0.14 μL/g in TG-Rx; P<0.008 for both). At day 28, EF was higher in TG (46.3%±2.9%) compared with WT and TG-Rx (32.7±2.3% and 33.7±2.3%, respectively; P<0.003 for both). Wall thickening at day 28 post-MI was greater in the base and mid-LV in TG than WT and TG-Rx. Noninfarcted region interstitial collagen was similar between groups. Thus, the NO pathway may mediate much of the benefits of cardiac AT2-R overexpression during post-MI remodeling. (Hypertension. 2004;43:1-6.)

Key Words: angiotensin ■ MRI ■ myocardial infarction ■ remodeling ■ nitric oxide ■ receptors ■ imaging

Most of the physiological effects of angiotensin (Ang) II are mediated through the angiotensin II type 1 receptor (AT1-R).1 However, the role of the angiotensin II type 2 receptor (AT2-R) in left ventricular (LV) remodeling in disease states is an area of active investigation.2–6 In fact, many of the beneficial effects of AT1-R blockade postmyocardial infarction (post-MI) or of angiotensin-converting enzyme (ACE) inhibitors may be mediated by Ang II stimulation of the AT2-R.7,8 We have previously demonstrated that AT2-R overexpression in the mouse heart preserves LV size and function during post-MI remodeling.9 The transgenic mice (TG) demonstrated preserved LV cavity size, wall thickness within the infarct zone, and regional and global LV function during post-MI remodeling compared with wild-type controls (WT). Others have shown that deletion of the AT2-R is detrimental post-MI, leading to myocardial rupture,10 heart failure, and increased mortality.10,11 Studies in vascular smooth muscle and the kidney suggest that the benefits of AT2-R stimulation may be through signaling pathways involving the kinin and nitric oxide (NO) system.12 AT2-R–mediated increases in cGMP caused by bradykinin and NO have been demonstrated in studies of the aorta and kidney,13,14 and blood pressure-lowering effects of AT1-R blockade involve AT2-R–mediated release of renal bradykinin and NO production.15 Recently, Ang II stimulation of the AT2-R in the TG model of cardiac overexpression was shown to attenuate perivascular fibrosis, an effect mediated through the kinin/NO system, without a change in cardiomyocyte hypertrophy.16 We hypothesized that the post-MI preservation of LV size and function seen with AT2-R overexpression in the mouse heart may be mediated by NO and involve changes in interstitial fibrosis.

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) and were approved by the University of Virginia Animal Care and Use Committee. The transgenic mouse strain with cardiac overexpression of the AT2 receptor in mice on a C57Bl/6 background yields approximately 22% to 37% AT2-R relative to AT1-R levels and were generously supplied by the laboratory of H.
Matsubara, MD, PhD. Transgene expression was assessed by Northern blot analysis of tail RNA and confirmed with sense and antisense PCR primers.

Twenty eight male TG mice and 11 age-matched male WT C57Bl/6 mice (Jackson Labs, Bar Harbor, ME) aged 10 to 14 weeks were studied before and at days 1 and 28 post-MI. Surgical procedures for infarct creation and reperfusion were reported previously.17

**CMR**

Anesthesia was induced with 3.0% inhaled isoflurane and maintained with 1.0% isoflurane administered via nosecone during imaging at baseline before MI (day 0) and days 1 (Figure 1) and 28 (Figure 2) post-MI. Details of CMR were previously published.9

**Treated Group**

Sixteen of the TG mice (TG-Rx) were treated with the NO synthase inhibitor N\(^{G}\)-nitro-L-arginine methyl ester (L-NAME) administered in the drinking water at 1 mg/mL from day 1 to day 28 post-MI. This dose has previously been shown to inhibit NO synthesis chronically while causing no significant increase in systemic blood pressure.12

**Noninvasive Hemodynamics**

Weekly noninvasive mean systolic blood pressures (SBPs) and heart rates (HRs) were measured in conscious mice using a tail-cuff apparatus (Visitech BP-2000 Analysis Systems).

**Histopathology**

After euthanizing the mice, the heart was removed and fixed in formaldehyde, embedded in paraffin, sectioned at 6 µm, and stained with picric acid Sirius red. Quantitative morphometry was performed on infarct border (adjacent) and remote myocardium in 5 TG, 5 TG-Rx, and 6 WT mice using an Olympus microscope with a green 540-nm filter and a CCD72 videocamera interfaced to a computer with a Universal Imaging Image 1/AT morphometry system (West Chester, Pa). A minimum of 35 fields approximately 575×750 µm each was measured from 3 or 4 sections from each region, and volume percent collagen calculated as the mean from all fields in each region for each animal.

**Results**

**Noninvasive Hemodynamics**

The mean SBP in conscious animals measured by a noninvasive tail-cuff apparatus were similar at baseline and there were no significant changes in the 3 groups between time points, although SBP tended to be higher in TG-Rx mice (101±5 at baseline to 112±4 mm Hg by day 28 post-MI) (Table 1). Mean HR in conscious mice was also similar between all 3 groups at baseline and each later time point (Table 1). Likewise, mean HR in sedated animals during CMR sessions was similar for all 3 groups (Table 2).

**Infarct Size**

Infarct size by contrast-enhanced CMR was similar in WT, TG-Rx, and TG mice: 41.1±1.4%, 40.5±1.7%, and 42.2±2.5% of LV mass, respectively (P=NS) (Figure 1).

**CMR Parameters at Baseline and During Post-MI Remodeling**

Left ventricular mass index was similar in all 3 groups at baseline (Table 2). There was a significant increase in LVMI in all 3 groups by day 28 post-MI, with no significant difference between the groups. At baseline, there was no significant difference in EDVI or ESVI between the 3 groups, and all 3 groups had a significant increase in EDVI and ESVI from day 0 to day 28 post-MI (Figures 3 and 4). By day 28

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**TABLE 1. Weekly Noninvasive Tail-Cuff Systolic Blood Pressures and Heart Rates**

<table>
<thead>
<tr>
<th></th>
<th>Week 0</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BP (mm Hg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>104±5</td>
<td>102±5</td>
<td>109±5</td>
<td>101±11</td>
</tr>
<tr>
<td>TG</td>
<td>109±12</td>
<td>101±7</td>
<td>112±5</td>
<td>112±5</td>
</tr>
<tr>
<td>TG-Rx</td>
<td>101±5</td>
<td>101±6</td>
<td>107±5</td>
<td>112±4</td>
</tr>
<tr>
<td><strong>HR (bpm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>598±26</td>
<td>637±23</td>
<td>681±23</td>
<td>666±33</td>
</tr>
<tr>
<td>TG</td>
<td>690±29</td>
<td>587±29</td>
<td>622±22</td>
<td>683±22</td>
</tr>
<tr>
<td>TG-Rx</td>
<td>672±23</td>
<td>590±26</td>
<td>607±23</td>
<td>628±19</td>
</tr>
</tbody>
</table>

*P=NS for all.*

BP indicates blood pressure; HR, heart rate; bpm, beats per minute; WT, wild-type; TG, transgenic; TG-Rx, transgenic treated with L-NAME.

**Image Analysis**

MR images were analyzed using the ARGUS (Siemens Medical Systems, Princeton, NJ) image analysis program to determine LV end-diastolic volume (EDV), end-systolic volume (ESV), ejection fraction (EF), LV mass (LVM), end-diastolic wall thickness (EDWT), and percent wall thickening (WT) at baseline and day 28 post-MI as previously reported. EDV, ESV, and LVM were indexed to body weight in grams (ESVI, EDVI, LVMI). The hyperenhanced area was planimetered, and infarct area calculated as a percentage of total LV mass (Figure 1).

**Statistical Analysis**

Changes in all parameters from day 0 to 28 post-MI between groups were compared using 2-way ANOVA with Tukey subtesting to analyze differences between groups and time points. Between-group differences in infarct size and regional percent volume collagen were analyzed using one-way ANOVA. All values are presented as mean±SE of mean.

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**Figure 1.** End-systolic short-axis Gd-enhanced cine MR images at day 1 post-MI in WT control (left), TG-Rx (center), and TG mice (right). Note similar hyper-enhanced infarct area in all 3 mice from 10 o’clock to 4 o’clock in the images.

**Figure 2.** End-systolic short-axis cine MR images without Gd at day 28 post-MI in WT control (left), TG-Rx (center), and TG mice (right). Note the increased end-systolic cavity area in the WT mouse and the L-NAME–treated TG mouse compared with the TG mouse, which has preserved wall thickness in the infarct zone and comparatively smaller end-systolic cavity size.
post-MI, EDVI was significantly lower in TG mice (2.56±0.19 μL/g) compared with WT (3.72±0.16 μL/g; *P<0.001) and TG-Rx mice (3.23±0.16 μL/g; *P<0.03) (Table 2, Figure 3). Similarly, at day 28 post-MI, ESVI was significantly lower in TG mice (1.41±0.17 μL/g) compared with WT (2.53±0.14 μL/g; *P<0.001) and TG-Rx mice (2.17±0.14 μL/g, *P<0.008) (Figures 2 and 4).

At baseline, EFs in TG and TG-Rx mice were similar but significantly higher than in WT mice (74.7%±2.2% and 69.9%±2.2% for TG and TG-Rx versus 61.4%±2.3% for WT; *P<0.03 versus WT). While all 3 groups had a significant decrease in EF from baseline to day 28 post-MI, by the latter time point EF was the same in WT and TG-Rx mice (32.7%±2.3% and 33.7%±2.3%, respectively), and significantly lower in TG mice (46.3%±2.8%; *P<0.001 versus WT and *P<0.003 versus TG-Rx) (Figure 5).

**Table 2. Global Parameters by CMR on Day 0 and Day 28 Post-MI**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WT</th>
<th>TG</th>
<th>TG-Rx</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (bpm)</td>
<td>443±22</td>
<td>456±21</td>
<td>448±18</td>
</tr>
<tr>
<td>LVMI (mg/g)</td>
<td>2.68±0.14</td>
<td>2.92±0.14</td>
<td>2.79±0.12</td>
</tr>
<tr>
<td>EDVI (μL/g)</td>
<td>1.76±0.16</td>
<td>1.46±0.15</td>
<td>1.83±0.13</td>
</tr>
<tr>
<td>ESVI (μL/g)</td>
<td>0.69±0.14</td>
<td>0.39±0.13</td>
<td>0.60±0.12</td>
</tr>
<tr>
<td>EF (%)</td>
<td>61.4±2.3</td>
<td>74.7±2.2</td>
<td>69.9±2.2</td>
</tr>
</tbody>
</table>

HR indicates heart rate; LVMI, left ventricular mass index; EDVI, end-diastolic volume index; ESVI, end-systolic volume index; EF, ejection fraction; WT, wild-type; TG, transgenic; TG-Rx, transgenic treated with L-NAME.

*P<0.001 vs day 0; †P<0.02 vs WT; ‡P<0.03 vs TG.

**Regional LV Size and Function Post-MI**

At baseline, regional wall thickness was similar between groups (Table 3). Wall thickening was greater at baseline than WT in the base in both TG groups, as shown previously.9 At day 28 post-MI, there was no significant change in regional EDWT in any of the 3 groups. However, percent thickening decreased significantly in the mid-ventricle and apex in all 3 groups and at the base in the TG-Rx group (Table 3). At day 28, percent thickening at the base was greater in TG (45.8%±5.7%) than the other 2 groups (23.1%±4.3% in WT and 23.2%±4.5% in TG-Rx; *P<0.008 for both). Similarly, in the mid-LV, percent thickening at the base was greater in TG (30.7%±4.6%) than WT (12.6%±3.5%; *P<0.009) and TG-Rx (11.9%±3.8%; *P<0.008). All groups demonstrated similarly reduced percent thickening within the apex (Table 3).

**Quantitative Collagen Analysis**

In day 28 post-MI hearts, there was no significant difference in mean collagen content within the adjacent (P=0.33) or remote regions (P=0.85) between the three groups. However, adjacent collagen content was greater than remote within each group (10.8%±2.1% versus 1.2%±0.4% in WT, *P<0.003; 13.9%±1.4% versus 1.5%±0.3% in TG, *P<0.001; and 13.7%±1.0% versus 1.3%±0.3% in TG-Rx, *P<0.001).

**Discussion**

This study confirms our previous findings that AT2-R overexpression in the heart offers protection against post-infarct LV remodeling. This benefit is largely abrogated by the use of the nitric oxide synthase antagonist, L-NAME. AT2-R overexpression was associated with lower EDVI, lower ESVI, and higher EF at day 28 post-MI than both WT controls and L-NAME–treated TG mice despite equivalent infarct sizes in the 3 groups. These parameters indicative of LV remodeling were similar between WT and L-NAME treated TG mice. Wall thickening at day 28 post-MI in the base and mid-LV was greater in TG mice than WT and the

![Figure 3](image1.png)  **Figure 3.** EDVI at baseline (day 0) and day 28 post-MI in all three groups. *P<0.001 vs baseline; †P<0.001 vs WT; ‡P<0.03 vs TG.

![Figure 4](image2.png)  **Figure 4.** ESVI at baseline (day 0) and day 28 post-MI. *P<0.001 vs baseline; †P<0.001 vs WT; ‡P<0.008 vs TG.
treated TG mice. Quantitative collagen in noninfarcted regions was similar between groups.

Thus, much of the beneficial effect of AT2-R overexpression is mediated through the NO pathway and is not explained by differences in interstitial collagen within noninfarcted regions. No significant effects of AT2-R overexpression or l-NAME therapy was seen on HR or blood pressure during the post-MI period, although BP tended to increase in treated mice. This suggests that hemodynamic effects alone do not account for these differences.

Therefore, the benefits of myocardial AT2-R overexpression may be caused by either changes in load and/or changes in myocyte size and function. Preload (LVEDVI) is reduced in TG compared with WT and TG-Rx, and this could impact on myocyte remodeling and global systolic function. Previous studies have shown in a rat model of chronic MI that myocyte function in noninfarcted regions is normal.18,19 We have shown in a large animal model that adjacent noninfarcted myocytes are dysfunctional and remote myocytes function normally.20 This regional heterogeneity of function in noninfarcted regions may be difficult to demonstrate in isolated myocytes from small animal models. In the present study, regional function in TG mice is better than WT and TG-Rx in the mid and basal LV (adjacent and remote regions), suggesting that load effects may be more important than myocyte effects per se.

Studies in models of targeted deletion of the AT2-R suggest that differences in the extent of fibrosis in the infarct region may account for increased rates of myocardial rupture in the knockout mice.10 Myocardial rupture is uncommon in the model used in the present study and may reflect differences in the genetic background of the mice. In the present study, no between-group differences in wall thickness or in wall thickening were noted in the apical infarct zone. All of the differences in these parameters were seen in noninfarcted regions in the mid-LV and base, without differences in interstitial collagen, arguing against the primary effect of the AT2-R on fibrosis.

AT2-R-mediated increases in cGMP and hypotensive effects caused by bradykinin and NO have been shown in the aorta of the spontaneously hypertensive rat.13 AT2-R effects in the kidney are also mediated by bradykinin and NO.14 The effects of AT1-R blockade on blood pressure are affected by the AT2-R through release of renal bradykinin, which then mediates NO production.15

Recent evidence suggests that the same pathways apply to myocardial AT2-R signaling. A specific AT2-R agonist, CPG 42112, increased eNOS expression in myocytes by 2.4-fold.21 eNOS expression was increased by direct Ang II stimulation and antagonized by the AT2-R antagonist PD 123319. In vivo, in AT2-R knockout mice, eNOS protein expression was significantly reduced. The upregulation of eNOS was mediated through a pathway involving calcineurin and nuclear factor of activated T cells.21 These studies suggest that Ang II stimulation of the AT2-R is responsible for increases in eNOS and resultant beneficial cardiac effects.

In rats with MI, NO inhibition with l-NAME led to a 22% decrease in LV dP/dt, without a change in mean arterial pressure or LV end-diastolic pressure, suggesting direct cardioinhibitory effects of NOS blockade.22 Specific iNOS antagonism with aminoguanidine in this model increased LV dP/dt, suggesting that iNOS activation is detrimental and eNOS activation is protective post-MI. Further evidence of the former is that iNOS knockouts demonstrated higher dP/dt, less apoptosis, and improved survival at 4 months post-MI compared with WT.23 Conversely, eNOS knockouts demonstrated lower EF, higher EDVs, and LV mass at 4 weeks post-MI than WT controls.24 eNOS may contribute to the

### TABLE 3. End-Diastolic Wall Thickness and Percent Wall Thickening at Baseline and Day 28 Post-MI

<table>
<thead>
<tr>
<th></th>
<th>End-Diastolic Wall Thickness (mm)</th>
<th>Percent Thickening (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>Mid</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>0.93±0.04</td>
<td>0.98±0.03</td>
</tr>
<tr>
<td>TG</td>
<td>0.85±0.04</td>
<td>0.90±0.03</td>
</tr>
<tr>
<td>TG-Rx</td>
<td>0.84±0.03</td>
<td>0.81±0.02</td>
</tr>
<tr>
<td><strong>Days 28</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT</td>
<td>0.93±0.04</td>
<td>0.90±0.03</td>
</tr>
<tr>
<td>TG</td>
<td>0.88±0.05</td>
<td>0.84±0.03</td>
</tr>
<tr>
<td>TG-Rx</td>
<td>0.88±0.04</td>
<td>0.82±0.03</td>
</tr>
</tbody>
</table>

WT indicates wild-type; TG, transgenic; TG-Rx, transgenic treated with l-NAME.

*P<0.001 vs baseline; †P<0.01 vs WT; ‡P<0.008 vs TG.
benefits of pharmacologic therapy as well. The eNOS knockouts demonstrated attenuated responses to ACE inhibition and AT2-R blockade compared with WT mice post-MI.\textsuperscript{25}

In a study of Ang II-induced hypertrophy and interstitial fibrosis in the same transgenic model as in the present study, there was significantly less Ang II-induced perivascular fibrosis of intramuscular coronary arteries in TG, and this inhibition of perivascular fibrosis was abolished by concomitant treatment with L-NAME.\textsuperscript{16} No difference in the extent of interstitial fibrosis was seen in the present study between WT, TG, or TG-Rx groups. This may relate to the differences between direct Ang II-mediated fibrosis and the multifactorial fibrosis induced after MI. No difference in fibrosis in noninfarcted regions was seen between WT and AT2-R knockout (KO) mice in a post-MI study.\textsuperscript{4} These investigators also noted similar increases in myocyte cross-sectional area in the 2 groups, suggesting that the increase in LV mass seen in the AT2-R knockouts post-MI could be caused by myocyte elongation characteristic of volume-overload hypertrophy.

Hemodynamics alone are probably not responsible for the effects of L-NAME in this model as no significant effect between groups on BP or HR was seen over the 28 days post-MI, although there was a trend toward increasing BP in the L-NAME group. In the vascular smooth muscle model of AT2-R overexpression, BP was only elevated by 11±1 mm Hg after 14 days of therapy with the same dose of L-NAME. It may be that overexpression of AT2-R protects against the hypertensive effect of L-NAME as a previous study demonstrated that AT2-R null mice demonstrated significantly greater blood pressure response to L-NAME than WT controls.\textsuperscript{26}

**Study Limitations**

If the dose of L-NAME were inadequate, NO synthase inhibition would have been incomplete, in which case remodeling would have been attenuated. However, in the vascular smooth muscle model of AT2-R overexpression, this dose of L-NAME completely antagonized the effects of the AT2-R without significantly altering blood pressure.\textsuperscript{12} Baseline LV function is known to be greater in TG mice than WT controls.\textsuperscript{9} However, in the TG-Rx mice, LV EF decreased to the same level as of WT controls by day 28 post-MI, suggesting that baseline differences were abolished by NO inhibition post-MI. Further work is necessary to understand the effects of AT2-R overexpression on myocyte size and function.

**Perspectives**

The AT2-R plays an increasingly well understood role in remodeling in myocardial disease states including volume and pressure overload hypertrophy. The specific mechanisms of benefit of commonly used pharmacologic agents after MI, including ACE inhibitors and AT1-R receptor blockers, are incompletely understood and may involve the AT2-R to a major extent. Understanding the mechanisms underlying the effects of the AT2-R on post-infarct remodeling will support the development of specific methods of manipulating levels of the AT2-R to limit remodeling. Future studies will use pharmacologic and genetic approaches to better understand the interplay between bradykinin and NO pathways as well as the cross-talk between the AT1-R and AT2-R.

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**References**


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