Increased Inducible Nitric Oxide Synthase Expression Contributes to Myocardial Dysfunction and Higher Mortality After Myocardial Infarction in Mice

Qingping Feng, MD, PhD; Xiangru Lu, MD; Douglas L. Jones, PhD; Ji Shen, MD; J. Malcolm O. Arnold, MD

**Background**—Inducible nitric oxide synthase (iNOS) is expressed in the myocardium after myocardial infarction (MI) and in heart failure. Its pathophysiological role in these conditions, however, is not clear. We hypothesized that increased NO production from iNOS expression causes myocardial dysfunction and results in higher mortality after MI.

**Methods and Results**—MI was induced by left coronary artery ligation in iNOS−/− mutant and wild-type mice. Mortality was followed up for 30 days. MI resulted in a significant increase in mortality in both iNOS−/− and wild-type mice compared with sham operation (P<0.01). Mortality was significantly decreased and LV myocardial contractility was increased, however, in iNOS−/− mice compared with the wild-type mice (P<0.05). Five days after MI, myocardial iNOS mRNA expression, plasma nitrate and nitrite concentrations, and myocardial plasma nitrotyrosine levels were significantly increased in wild-type compared with iNOS−/− mutant mice (P<0.05). Both basal LV +dP/dt and its response to dobutamine were significantly increased in iNOS−/− compared with the wild-type mice (P<0.05).

**Conclusions**—Increased NO production from iNOS expression contributes to myocardial dysfunction and mortality after MI in mice. (Circulation. 2001;104:700-704.)

**Key Words:** heart failure • nitric oxide • nitric oxide synthase • myocardial infarction

Nitric oxide (NO) is produced from L-arginine by a family of NO synthases. Three distinct isoforms of nitric oxide synthase (NOS), derived from separate genes, are neural NOS (nNOS), inducible NOS (iNOS), and endothelial NOS (eNOS).1 Whereas eNOS and nNOS are calcium-dependent enzymes and produce small amounts of NO on stimulation, iNOS is a calcium-independent enzyme often induced by cytokines and produces high levels of NO. Basal generation of NO by eNOS plays an important role in the regulation of basal vascular tone, blood pressure, and tissue perfusion.2,3 High levels of NO produced by activated macrophages not only may be toxic to undesired microbes, parasites, or tumor cells but also may harm healthy cells.1

Cardiac myocytes have been demonstrated to produce iNOS protein and activity within several hours of treatment with cytokines.4 Recent studies have shown that iNOS expression and activity are increased in the myocardium of failing hearts and result in increased NO levels in the circulation.5–9 Although increased NO production from iNOS may decrease vascular resistance, which is beneficial, high levels of NO may also depress myocardial contractility and, through formation of peroxynitrite, may cause myocardial damage.10 In the present study, we hypothesized that increased NO production from iNOS expression causes myocardial dysfunction and results in high mortality after myocardial infarction (MI). To test this hypothesis, we occluded the left coronary artery in iNOS−/− mutant and wild-type mice and investigated the role of iNOS in myocardial dysfunction and disease progression after MI.

**Methods**

**Animals**

Animals used in this study were handled in accordance with the guidelines of the Animal Care Committee at the University of Western Ontario, Canada. Breeding pairs of iNOS−/− mutant and C57BL6 wild-type mice were purchased from Jackson Laboratory. A breeding program was carried out to produce adult mice (age 3 to 6 months) for the experiments. Mice were genotyped by a polymerase chain reaction (PCR) method using genomic DNA extracted from the tail.

**Induction of MI**

Mice were randomly selected to undergo coronary artery ligation or sham surgery by a technique similar to that described in rats.5,11 Mice were anesthetized with sodium pentobarbital (50 mg/kg IP). Atropine (0.05 mg SC) was administered to reduce airway excretion. Animals were intubated and artificially ventilated with a respirator (SAR-830, CWE, Inc.). A left intercostal thoracotomy was performed. After the pericardium had been opened, the left coronary artery was ligated by a suture. The lungs were then hyperinflated.
and the thorax was closed. Sham-operated mice underwent the same surgery minus the coronary artery ligation. The infarct size was measured at the end of the experiment and was expressed as a fraction of the total cross-sectional endocardial circumference of the left ventricle (LV).5,11

**Hemodynamic Measurements**

Mice were anesthetized with sodium pentobarbital (50 mg/kg IP) for catheter placements. The right carotid artery was cannulated with a Millar tip transducer catheter (model SPR-261, 1.4F). After arterial blood pressure and heart rate measurements were obtained, the catheter was advanced to the LV for measurement of LV systolic and end-diastolic pressures as well as the maximal rate of pressure development (+dP/dt) and rate of relaxation (−dP/dt) of LV.

**Isolated Heart Preparation**

Mice were killed by cervical dislocation. Hearts were rapidly removed and placed on a Langendorff apparatus perfused with Krebs solution at 37°C. Contractility was measured by use of ultrasound crystals.12 The advantage of this technique over the classic Langendorff preparation in studying infarcted hearts is that a balloon is not required in the LV chamber. LV pressures were monitored by a fluid-filled catheter connected to a pressure transducer. Both atria were cut open to drain perfusate. The crystals (0.7 and 1.0 mm) were fixed on the heart surface to allow long- and short-axis measurement. The ultrasound and pressure signals were measured by a Digital Sonomicrometer (Sonometrics). Maximum and minimum distances as well as percent shortening were calculated.12

**Nitrate/Nitrite Assay**

Plasma nitrate/nitrite (NOx) levels were measured as we previously described. Briefly, nitrate was converted to nitrite with Aspergillus nitrate reductase, and the total nitrite was measured with the Griess reagent. The absorbance was determined at 540 nm with a spectrophotometer.

**Nitrotyrosine Measurements**

Nitrotyrosine, the fingerprint of peroxynitrite in the myocardium, was determined by ELISA according to the manufacturer’s instructions (Cayman Chemical). Briefly, the noninfarcted LV myocardium was homogenized, and the supernatant was obtained. Plasma and tissue supernatant were concentrated to 2 to 4 times before they were incubated overnight with anti-nitrotyrosine rabbit IgG (Chemicon International) and nitrotyrosine acetylcholinesterase tracer in pre-coated (mouse anti-rabbit IgG) microplates followed by color development with Ellman’s reagent. The absorbance was measured at 405 nm. Intra-assay and interassay variabilities were 7% and 9%, respectively. To determine cellular localization of nitrotyrosine in the myocardium, immunohistochemical staining was performed in paraffin-embedded sections of the heart by use of the same antibodies as above. Sections were counterstained with hematoxylin.

**Reverse Transcription–PCR**

Total RNA was isolated from the noninfarcted LV myocardium with TriZol reagent and reverse transcribed into first-strand cDNA by use of the Moloney murine leukemia virus reverse transcriptase (RT) system. The cDNAs of iNOS and GAPDH were amplified by PCR with the same primers and conditions as we described previously.13 Equal aliquots of cDNA were amplified for 38 and 20 cycles for iNOS and GAPDH, respectively. PCR products of iNOS (189 bp) and GAPDH (297 bp) were electrophoresed in 1.5% agarose gels.

**Statistical Analysis**

Data were expressed as the mean ± SEM. ANOVAs were performed with the Student-Newman-Keuls test to detect significance in multiple groups or Student’s t test between 2 groups. Survival was analyzed by the method of Kaplan and Meier. Differences were considered significant at the level of P < 0.05.

---

**TABLE 1. General Characteristics of iNOS−/− and Wild-Type Mice Subjected to MI or Sham Operation**

<table>
<thead>
<tr>
<th></th>
<th>MI Wild</th>
<th>iNOS−/− Wild</th>
<th>MI Wild</th>
<th>iNOS−/− Wild</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>58</td>
<td>58</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Sex, M/F</td>
<td>53/5</td>
<td>52/6</td>
<td>9/1</td>
<td>12/2</td>
</tr>
<tr>
<td>Age, d</td>
<td>100±5</td>
<td>97±5</td>
<td>121±26</td>
<td>110±13</td>
</tr>
<tr>
<td>Body weight, g</td>
<td>27.0±0.4</td>
<td>28.1±0.5</td>
<td>26.6±0.8</td>
<td>28.9±1.0</td>
</tr>
<tr>
<td>Infarct size, %</td>
<td>33.8±0.8</td>
<td>35.1±0.9</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note, there was no statistical difference between iNOS−/− and wild-type mice in any of the above parameters within the MI or sham group.

**Results**

**Mortality After MI**

A total of 99 wild-type and 97 iNOS−/− mice were subjected to MI or sham operation. Animals were excluded from analysis for 2 reasons: (1) perioperative death, within the first 24 hours after surgery (28 wild-type and 23 iNOS−/−) or (2) infarct size <20% of the LV (3 wild-type and 2 iNOS−/−). The remaining 68 wild-type and 72 iNOS−/− mice were included in the study, and their mortality was followed up for 30 days after surgery. General characteristics of these animals are shown in Table 1. There were no differences in age, sex, body weight, or infarct size between iNOS−/− mutant and wild-type mice subjected to MI (P = NS). MI resulted in a significant increase in mortality in both iNOS−/− and wild-type mice compared with sham operation (P < 0.001, Figure 1). The 30-day survival in iNOS−/− mice (58.6%, or 34/58), however, was significantly increased compared with the wild-type mice (37.9%, or 22/58, P = 0.034, Figure 1).

Thirty days after MI, plasma NOx levels were significantly increased in the wild-type mice (Table 2). There were no significant differences in infarct size, heart rate, mean arterial pressure, or LV systolic pressure between iNOS−/− and wild-type mice. LV dp/dt, however, was increased in iNOS−/− compared with the wild-type mice (P < 0.01, Table 2). Myocardial contractile function after MI was also studied in a modified Langendorff preparation. Basal LV end-diastolic pressure was 0.2±0.4 and 0.5±0.5 mm Hg in wild-type and iNOS−/− mice (n=3 per group, respectively). In response to dobutamine 3 μg/mL, LV end-diastolic pressure was −0.2±0.6 and 0.5±0.5 mm Hg in wild-type and iNOS−/− mice (n=3 per group).

---

**Figure 1. Survival after MI in iNOS−/− mutant and wild-type mice. Animals were followed up for 30 days after surgery. Post-MI survival was significantly increased in iNOS−/− mutants (n=58) vs wild-type mice (n=58, P<0.05). There was no significant difference in survival after sham operation between iNOS−/− (n=14) and wild-type (n=10) mice.**
was significantly increased in iNOS
myocardial function, iNOS mRNA expression, and plasma NO\textsubscript{x}
infarcted myocardium of wild-type mice after MI. Consistent
mRNA expression was present, however, in the non-
response to dobutamine.

### TABLE 3. Percent Shortening in Isolated Hearts From iNOS\textsuperscript{−/−} and Wild-Type Mice 30 Days After MI

<table>
<thead>
<tr>
<th>Infarct Size, %</th>
<th>Baseline</th>
<th>Dobutamine 1 μg/mL</th>
<th>Dobutamine 3 μg/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Long Axis</td>
<td>Short Axis</td>
</tr>
<tr>
<td>Wild, n=6</td>
<td>34±4</td>
<td>0.90±0.10</td>
<td>1.18±0.15</td>
</tr>
<tr>
<td>iNOS\textsuperscript{−/−}, n=6</td>
<td>33±3</td>
<td>1.38±0.18</td>
<td>1.93±0.33</td>
</tr>
<tr>
<td>P</td>
<td>NS</td>
<td>&lt;0.05</td>
<td>0.08</td>
</tr>
</tbody>
</table>

HR indicates spontaneous heart rate. Data were compared by unpaired Student’s t test between wild-type and iNOS\textsuperscript{−/−} mice.
A number of cellular constituents of cardiac muscle, including the endothelium and smooth muscle of the cardiac microvasculature, the endocardial endothelium, and cardiac myocytes, are now known to be capable of expressing iNOS in response to lipopolysaccharide and specific cytokines. Myocardial iNOS expression has been demonstrated in humans and animals with induced heart failure regardless of pathogenesis. Consistent with this notion, the present study showed a marked iNOS expression in the noninfarcted area of the LV myocardium after MI in the wild-type mice. Mechanisms of the increased iNOS expression and NO production after MI are still not fully understood. Cytokines such as tumor necrosis factor-α are increased in rats with MI and in patients with heart failure. Many factors, such as activation of angiotensin II and α-adrenergic receptors, may also promote iNOS expression in cardiac myocytes after MI.

Myocardial iNOS induction has been demonstrated to cause contractile dysfunction in various preparations, including isolated myocytes, isolated perfused working hearts, and in vivo animal preparations. NO produced by iNOS within cardiac myocytes is reported to be responsible for diminished inotropic responsiveness to isoproterenol in an autocrine and/or paracrine fashion. Our recent studies have demonstrated that iNOS expression has been demonstrated in humans and animals with induced heart failure regardless of pathogenesis. Cytokines such as tumor necrosis factor-α are increased in rats with MI and in patients with heart failure. Many factors, such as activation of angiotensin II and α-adrenergic receptors, may also promote iNOS expression in cardiac myocytes after MI.

Nitrotyrosine levels in wild-type and iNOS−/− mutant mice 5 days after MI. A through E, Immunohistochemical staining of nitrotyrosine. Negative controls (A) were performed without anti-nitrotyrosine antibody. Anti-nitrotyrosine antibody (1:50) was preincubated with nitrotyrosine (200 μmol/L, B) or tyrosine (200 μmol/L, C) for 1 hour at room temperature before antibody was incubated with tissue section. Tissues in A through D were all from wild-type mice. Representative nitrotyrosine staining in noninfarcted LV myocardium from wild-type (D) and iNOS−/− mutant (E) mice.

Discussion

The main finding of the present study was the significant increase of survival after MI in iNOS−/− mutants compared with the wild-type mice. After MI, iNOS expression was induced in the LV myocardium and resulted in elevations of NO and nitrotyrosine levels in the wild-type compared with the iNOS−/− mutant mice. Furthermore, increases in NO production and nitrotyrosine levels in the wild-type mice were associated with decreased myocardial function. The results suggest that increased NO production and peroxynitrite formation from iNOS expression contribute to myocardial dysfunction and heart failure progression in mice after MI.

![Figure 3](image_url)

**Figure 3.** Nitrotyrosine levels in wild-type and iNOS−/− mutant mice 5 days after MI. A through E, Immunohistochemical staining of nitrotyrosine. Negative controls (A) were performed without anti-nitrotyrosine antibody. Anti-nitrotyrosine antibody (1:50) was preincubated with nitrotyrosine (200 μmol/L, B) or tyrosine (200 μmol/L, C) for 1 hour at room temperature before antibody was incubated with tissue section. Tissues in A through D were all from wild-type mice. Representative nitrotyrosine staining in noninfarcted LV myocardium from wild-type (D) and iNOS−/− mutant (E) mice.

LV + dP/dt was significantly enhanced in iNOS−/− compared with the wild-type mice (P<0.05, Figure 4A). In response to dobutamine 4 μg/kg IV, the increase of LV + dP/dt was significantly enhanced in iNOS−/− compared with the wild-type mice (P<0.05, Figure 4B). Basal and dobutamine-stimulated LV − dP/dt were not statistically different between the 2 groups (P=NS).

![Figure 4](image_url)

**Figure 4.** LV + dP/dt in iNOS−/− and wild-type mice 5 days after MI. A, Basal levels of LV + dP/dt. B, Increases of LV + dP/dt after dobutamine (4 μg/kg IV). n=7 to 8 per group. *P<0.05, **P<0.01 vs wild-type mice.
nitrone levels, the fingerprints of peroxynitrite, were significantly increased in the LV myocardium and plasma of wild-type mice after MI compared with iNOS−/− mice. Our results support the notion the peroxynitrite is involved in the myocardial dysfunction in mice with MI.

Formation of peroxynitrite depends on the balance between local concentrations of NO, O₂⁻, and superoxide dismutase (SOD). In the isolated perfused hearts, a 3-fold increase in NO production was associated with <1-fold increase in nitrone formation, clearly indicating that other factors, not just NO, contribute significantly to the formation of peroxynitrite. In the present study, marked NO production was associated with only a moderate increase (35% to 46%) in nitrone in wild-type mice after MI. The reason for this is not clear. SOD is increased over, myeloperoxidase and horseradish peroxidase also oxidize nitrone in the presence of H₂O₂ into species able to nitrate tyrosine. These mechanisms may explain a moderate increase in peroxynitrite production and nitrone formation in the present study. Factors that contributed to basal levels of nitrone in the myocardium and plasma of iNOS−/− mice are not known. Reactive species, such as nitrogen dioxide and acidified nitrate, can produce nitrone. Moreover, myeloperoxidase and horseradish peroxidase also oxidize nitrone in the presence of H₂O₂ into species able to nitrate tyrosine. The contribution of these factors to the production of nitrone after MI requires further investigation.

In summary, MI results in myocardial iNOS expression and NO production and higher nitrone levels, leading to myocardial dysfunction and increased mortality. Further studies are necessary to investigate the therapeutic potential of inhibiting iNOS activity versus reducing peroxynitrite formation in heart failure.

Acknowledgments

This study was supported by research grants awarded to Dr Feng from the Canadian Institutes of Health Research (MT-14653) and the Heart and Stroke Foundation of Ontario (T-4045). Dr Feng was supported by a Research Career Award from the Pharmaceutical Manufacturers Association of Canada Health Research Foundation and the Canadian Institutes of Health Research.

References