Induction of Heme Oxygenase-1 In Vivo Suppresses NADPH Oxidase–Derived Oxidative Stress

Srinivasa R. Datla, Gregory J. Dusting, Trevor A. Mori, Caroline J. Taylor, Kevin D. Croft, Fan Jiang

Abstract—Our previous studies suggest that heme oxygenase (HO)-1 induction and/or subsequent bilirubin generation in endothelial cells may suppress superoxide generation of from reduced nicotinamide-adenine dinucleotide phosphate (NADPH) oxidase. In this study, we examined the consequence of HO-1 induction in vivo on NADPH oxidase activity. Three doses of hemin (25 mg · kg⁻¹, IP, every 48 hours), with or without cotreatment with the HO inhibitor tin protoporphyrin-IX (15 mg · kg⁻¹, IP), were given to apolipoprotein E–deficient mice, which display vascular oxidative stress. Hemin treatment increased HO-1 expression and activity in aorta (undetectable at baseline) and kidney (by 3-fold) and significantly reduced both NADPH oxidase activity (by ≈25% to 50%) and superoxide generation in situ. The increase in HO-1 activity and inhibition of NADPH oxidase activity by hemin were reversed by tin protoporphyrin-IX and were not associated with changes in Nox2 or Nox4 protein levels. Hemin also reduced plasma F₂-isoprostane levels by 23%. The inhibition of NADPH oxidase activity by hemin in the aorta was mimicked by bilirubin in vitro (0.01 to 1 μmol/L). Bilirubin also concentration-dependently reduced NADPH oxidase–dependent superoxide production stimulated by angiotensin II in rat vascular smooth muscle cells and by phorbol 12-myristate 13-acetate in human neutrophil-like HL-60 cells. HO-1 overexpression by plasmid-mediated gene transfer in rat vascular smooth muscle cells decreased NADPH-stimulated superoxide production. Thus, systemic expression of HO-1 suppresses NADPH oxidase activity by mechanisms at least partly mediated by the bile pigment bilirubin, thereby reducing oxidative stress. (Hypertension. 2007;50:636-642.)

Key Words: bilirubin ■ heme oxygenase-1 ■ NADPH oxidase ■ oxidative stress ■ reactive oxygen species

Reduced nicotinamide-adenine dinucleotide phosphate (NADPH) oxidase expressed in nonphagocytic cells has a critical role in influencing the redox balance in vasculature. This enzyme consists of the membrane-bound Nox and p22phox subunits, the cytosolic p47phox and p67phox subunits, and a small GTPase, Rac. Activation of this enzyme results in a multicomponent electron transfer machinery that carries single electron from NADPH to molecular oxygen, yielding a superoxide anion.1 Excess superoxide generation in the vasculature decreases the availability of endothelial NO, resulting in endothelial dysfunction.2 Superoxide and derivative reactive oxygen species (ROS) promote lipid peroxidation, foam cell formation, and expression of proinflammatory molecules in vascular cells.3,4 Mounting evidence indicates that NADPH oxidase is involved in vascular oxidative stress and dysfunction in a variety of conditions, such as hyperlipidemia, diabetes mellitus, atherosclerosis, and hypertension.5,6 Increased oxidative stress in vascular tissues stimulates the expression of heme oxygenase (HO)-1, the inducible form that is the rate-limiting enzyme in heme degradation and production of the bile pigment bilirubin.7 HO-1 induction has potent protective actions against ROS-induced oxidative damage both in vitro and in vivo.8–10 Moreover, increased expression of HO-1 and subsequent bilirubin production may modulate endogenous cellular ROS generation. In reconstituted neutrophil NADPH oxidase, it has been reported that bilirubin inhibited the enzymatic superoxide production.11 Recently, Taille et al12 have demonstrated that HO-1 expression in macrophages inhibited NADPH oxidase activity through decreased heme availability and Nox2 protein abundance. It has also been suggested that activation of the HO-1/bilirubin pathway may interact with ROS generating systems in vascular tissues. For example, HO-1 expression reduced NADPH-dependent ROS production in vascular endothelial cells, and this effect was blocked by the HO-1 inhibitor tin protoporphyrin-IX (SnPP) and mimicked by bilirubin.13 We recently found that NO donors can suppress NADPH oxidase activity in cultured endothelial cells via induction of HO-1, which has implications for the vascular protective actions of NO donors.14 However, the effects of HO-1 expression in vivo on vascular ROS production, especially the NADPH oxidase activity, have not been examined. In the present study, we have investigated the systemic effects of HO-1 induction on NADPH oxidase activity in hyperlip-
idemic apolipoprotein (E)-deficient (ApoE0) mice, which exhibit increased oxidative stress.

Materials and Methods
An expanded Methods section is available online at http://hyper.ahajournals.org.

Cell Culture
Rat aortic smooth muscle cells (RASMCs)15 and HL-60 cells16 were cultured as described previously.

Animal Treatment and Sample Collection
All of the animal studies were carried out in accordance with the guidelines of the institutional animal ethics committee and the National Health and Medical Research Council of Australia. Male ApoE0 mice maintained on normal diet until 26 to 30 weeks of age were used. Animals were randomly divided into 3 groups: vehicle (control), hemin (3× IP injections at 25 mg·kg⁻¹, every 48 hours), and hemin plus SnPP (3× IP injections at 15 mg·kg⁻¹, every 48 hours). Twenty-four hours after the last injection, animals were euthanized, and blood, aorta, and kidney samples were collected. Plasma was quickly separated and stored at ~80°C for bilirubin and isoprostane analysis.

Lucigenin Enhanced Chemiluminescence
NADPH oxidase activity in cells and tissues was assessed by lucigenin-enhanced chemiluminescence as described previously.15

In Situ Superoxide Detection
Dihydroethidium (DHE) fluorescence was used to detect in situ superoxide levels as described previously.17,18

HO-1 Activity Assay
HO-1 activity in microsomal preparations from the kidney and aorta was measured by bilirubin generation according to the method described by Nath et al.19

Plasma F2-Isoprostane Measurement
Plasma F2-isoprostane levels were measured by capillary gas chromatography and electron capture negative ionization mass spectrometry as described previously.20

Plasma Bilirubin Measurement
Plasma bilirubin levels were determined using a total bilirubin kit (Thermo Electron Corporation) following the protocol provided by the manufacturer.

HO-1 Overexpression
The full-length cDNA of human HO-1 was purchased from OriGene Technologies. A nonexpression vector containing human HO-1 cDNA was used as the control.21

Statistical Analysis
Data are expressed as mean±SEM. Statistical significance (P<0.05) between the experimental groups was determined by unpaired Student’s t test or 1-way ANOVA, as appropriate.

Results
Hemin Induces HO-1 Expression and Activity In Vivo
In ApoE0 mice maintained on normal diet, the NADPH oxidase–dependent superoxide production was increased in the aorta as compared with wild-type controls (199±51 count per second per mg in ApoE0 versus 75±18 count per second per mg in C57BL/6; P<0.05; n=6). Although oxidative stress, per se, can induce HO-1 expression,22 in Western blot experiments, we found that HO-1 expression in the aorta and kidney from these ApoE0 mice was extremely low, suggesting that the increase in oxidative stress in these mice was not sufficient to induce HO-1 expression. In contrast, hemin administration caused a significant increase in HO-1 expression,22 whereas the levels of Cu/Zn superoxide dismutase were not changed. Cotreatment with the HO-1 inhibitor SnPP seemed to enhance the HO-1 expression, but this effect was not significant (Figure 1). Immunohistochemistry confirmed the enhanced HO-1 expression by hemin and demonstrated that HO-1 was mainly localized in the medial layers of aorta (Figure S1). In the aorta, HO-1 activity was undetectable under basal conditions; treatment with hemin markedly increased HO-1 activity, which was inhibited by SnPP (Figure 2B). The plasma bilirubin level was also significantly increased by hemin treatment (0.27±0.04 mg/dL in control versus 0.53±0.07 mg/dL in hemin-treated ones; P<0.05; n=12), and this was reversed

![Figure 1](http://hyper.ahajournals.org/)
by SnPP (0.30±0.05 mg/dL; \( P > 0.05 \) versus control; \( n = 7 \)). None of the treatments had any effect on body weight (30.7±0.6, 31.3±0.5, 31.3±0.8, and 31.0±0.4 g in control, hemin, hemin plus SnPP, and SnPP alone groups, respectively; \( n = 8 \) to 15).

HO-1 Expression Suppresses NADPH Oxidase Activity and In Situ Superoxide Production

NADPH oxidase activity in both aorta and kidney was reduced in hemin-treated mice (Figure 2), and this was reversed by SnPP (Figure 2). In both tissues, SnPP alone did not significantly alter the NADPH oxidase function (Figure 2). As found previously,\(^{15}\) the NADPH-stimulated superoxide release was blocked by the NADPH oxidase inhibitor diphenylenedioimid (DPI) but not affected by the NO synthase inhibitor \( \text{N}^\text{G} \)-nitro-L-arginine methyl ester, the xanthine oxidase inhibitor allopurinol, the mitochondrial electron transport chain inhibitor rotenone, the cyclooxygenase inhibitor indomethacin, or the cytochrome P450 inhibitor 17-octadecynoic acid (data not shown). Consistent with the decreased NADPH oxidase activity, in situ superoxide production measured by DHE fluorescence was also significantly reduced in tissues from hemin-treated animals, and SnPP blocked this effect of hemin (Figure 3 and Figure S2).

To confirm the source of superoxide detected by DHE fluorescence, we incubated aortic segments ex vivo in solutions containing various inhibitors before sectioning. As shown in Figure S3, the DHE fluorescence was reduced by the NADPH oxidase inhibitor DPI but not affected by other enzyme inhibitors.

Hemin Decreases Plasma \( \text{F}_2\)-Isoprostanes and Increases the Nitrate/Nitrite Level

We examined whether HO-1 expression affected measures of systemic oxidative stress. As shown in the Table, the plasma \( \text{F}_2\)-isoprostane levels were significantly decreased in hemin-treated animals. Interestingly, SnPP alone also reduced plasma \( \text{F}_2\)-isoprostanes. On the other hand, hemin treatment did not further change the plasma \( \text{F}_2\)-isoprostanes in the presence of SnPP (Table). We also measured the plasma nitrate/nitrite level. Interestingly, we found that there was a slight increase in the nitrate/nitrite level in the hemin-treated group (Table).

HO-1 Expression Does Not Affect Nox Expression

We also investigated whether HO-1 induction had an impact on the protein abundance of the heme-containing Nox sub-

![Figure 2](http://hyper.ahajournals.org/content/638/10/638/suppl/DC1)

**Figure 2.** Effects of in vivo treatment with vehicle (Con) or hemin (H) with or without SnPP (S) in ApoE\(^{\text{\textregistered}}\) mice on enzymatic activities of HO-1 (A and B) and NADPH oxidase (C and D) in aorta (A and C) and kidney (B and D). HO-1 activity was measured by bilirubin production using total homogenates (aorta, pooled samples from 6 animals in each group) or purified microsomes (kidney, \( n = 5 \) to 7), and expressed as nanomoles of bilirubin per milligram of protein per hour. NADPH oxidase activity was assessed by 100 \( \mu \text{mol/L} \) of NADPH-stimulated superoxide production detected with lucigenin-enhanced chemiluminescence, which was measured in counts per second (CPS) per milligram of tissue and expressed as percentage of the mean value of the control group (\( n = 5 \) to 8).

![Figure 3](http://hyper.ahajournals.org/content/638/10/638/suppl/DC2)

**Figure 3.** In situ superoxide levels in tissue sections of the aorta (A) and kidney (B) from ApoE\(^{\text{\textregistered}}\) mice treated with vehicle (Con), hemin, or hemin plus SnPP. Fluorescence intensity was quantified by measuring the area-normalized optical density (O.D.) using Image J software (\( n = 4 \) to 9).
units of NADPH oxidase. In the aorta, the Nox2 isoform could be readily detected, whereas in the kidney, only Nox4 was detectable. Nox1 was not detected with Western blot in either of these tissues. Hemin treatment with or without SnPP had no significant effect on the levels of either Nox2 in aorta or Nox4 in the kidney (Figure 4).

**Bilirubin Inhibits NADPH Oxidase Activity in Both Vascular and Phagocytic Cells**

To explore whether the inhibitory effect of HO-1 on NADPH oxidase activity could be mediated by its end product, bilirubin, we carried out ex vivo experiments using isolated aortic rings from untreated ApoE−/− mice. Preincubation of the tissues with bilirubin (10 nmol/L to 1 μmol/L) significantly inhibited the NADPH oxidase activity in a time- and concentration-dependent manner (Figure 5). To determine whether bilirubin had a similar effect on phagocytic NADPH oxidase, we used HL-60 cells. Stimulation of HL-60 cells with phorbol 12-myristate 13-acetate triggered a sustained superoxide release, which was blocked by the NADPH oxidase inhibitor DPI and significantly reduced by bilirubin (30 nmol/L to 1 μmol/L) in a concentration-dependent manner (Figure 5). The superoxide-scavenging effect of bilirubin is relatively weak (IC50 = 75 μmol/L) as compared with the concentrations used in this study, and to exclude that ROS are scavenged by bilirubin directly, we repeated the experiments in HL-60 cells that had been washed extensively after bilirubin pretreatment. Indeed, the inhibitory effect was largely preserved ≥20 minutes after removing bilirubin from the assay medium (online Figure S4).

**Bilirubin Inhibits Angiotensin II–Induced NADPH Oxidase Activation in Vascular Smooth Muscle Cells**

We also tested whether bilirubin could suppress NADPH oxidase activation under pathophysiological conditions using cultured RASMCs stimulated by angiotensin II (Ang II). Ang II significantly increased the NADPH-stimulated superoxide production (Figure 6). In all of the experiments, no chemiluminescence signal above the background could be detected in the presence of the NADPH oxidase inhibitor DPI. Preincubation of the cells with bilirubin (0.03 to 10 μmol/L) concentration-dependently reduced NADPH oxidase–dependent superoxide production in both resting (Figure 6A) and Ang II–treated cells (Figure 6B). Notably, the NADPH oxidase activity in Ang II–treated cells was decreased to a level comparable to that in resting cells in the presence of bilirubin from 0.3 to 10 μmol/L, which was also confirmed with DHE fluorescence microscopy (online Figure S5).

**Table 1. Effects of Hemin ± SnPP on Plasma F2-Isoprostanes and Nitrate/Nitrite Levels**

<table>
<thead>
<tr>
<th>Plasma Concentration</th>
<th>Vehicle</th>
<th>Hemin</th>
<th>Hemin + SnPP</th>
<th>SnPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>F2-isoprostanes, nmol/L</td>
<td>3.8 ± 0.2</td>
<td>2.9 ± 0.1*</td>
<td>2.2 ± 0.2*</td>
<td>2.6 ± 2.2*</td>
</tr>
<tr>
<td>Nitrate/nitrite, μmol/L</td>
<td>33.6 ± 2.3</td>
<td>48.3 ± 5.6*</td>
<td>34.9 ± 3.0</td>
<td>36.2 ± 1.1</td>
</tr>
</tbody>
</table>

*The plasma nitrate/nitrite was measured by the Griess reaction. *P < 0.05 vs vehicle control; n = 5 to 10.

**Figure 4.** Effects of hemin or hemin plus SnPP administration in ApoE−/− mice on Nox protein expression in the aorta (A) and kidney (B) measured with Western blot. The Nox2 isoform was readily detected in the aorta, whereas Nox4 was the predominant isoform in the kidney. C, Quantitated densitometry data normalized to β-actin (n = 3 to 4).

**Figure 5.** Effects of bilirubin on NADPH oxidase activity in isolated aortic rings of ApoE−/− mice (A; n = 5) and DMSO-differentiated (1.5% for 3 to 4 days), neutrophil-like HL-60 cells (B; n = 3). Tissue or cells were incubated with bilirubin of increasing concentrations. The NADPH oxidase activity in aortic rings was assessed by 100 μmol/L of NADPH-stimulated superoxide. The NADPH oxidase in HL-60 cells was activated with phorbol 12-myristate 13-acetate (PMA; 100 ng/mL, added at time 0). The NADPH oxidase inhibitor DPI (10 μmol/L) was used as a positive control. In both experiments, the superoxide was detected with lucigenin-enhanced chemiluminescence. Data are expressed as mean ± SEM.
dependent superoxide production. This may be an important mechanism underlying the cardiovascular protective effects of HO-1 and bilirubin that have been proposed by a number of studies. In vivo. The inhibitory effect of HO-1 was observed in both vascular smooth muscle cells under basal conditions and after Ang II treatment (B). The NADPH oxidase activity was assessed by 100 μmol/L of NADPH-stimulated superoxide. Ang II (100 nmol/L) was added acutely for 10 minutes before the chemiluminescence assay. Bilirubin or DPI was added 30 minutes before assay. *P<0.05 vs control; †P<0.05 vs Ang II alone-treated cells (n=3).

HO-1 Overexpression Inhibits NADPH Oxidase Activity in Vascular Smooth Muscle Cells

To further confirm that HO-1 expression has an inhibitory effect on vascular NADPH oxidase and to eliminate any nonspecific effects of hemin, per se, we overexpressed human HO-1 in RASMCs. As shown in online Figure S6A and S6B, transfection of the cells with a mammalian expression plasmid vector containing the full-length cDNA of human HO-1 significantly increased HO-1 expression, and this was accompanied by a decrease of NADPH oxidase activity (online Figure S6C).

Discussion

In this article, we provide direct evidence that HO-1 modulates NADPH oxidase activity and superoxide production in vivo. The inhibitory effect of HO-1 was observed in both aorta and kidney, tissues in which NADPH oxidase activation is a major source of oxidative stress. These in vivo data complement the reported inhibitory actions of HO-1 on NADPH oxidase function in macrophages and are in agreement with our own studies in human endothelial cells showing that HO-1 expression suppresses NADPH oxidase-dependent superoxide production. This may be an important mechanism underlying the cardiovascular protective effects of HO-1 and bilirubin that have been proposed by a number of animal and human studies.

Atherosclerotic plaques are present in the aorta from ApoE−/− mice, and these lesions show significant monocyte/macrophage infiltration, making it difficult to precisely define the cellular site of suppression of NADPH oxidase function. In measuring aortic NADPH oxidase activity, we deliberately chose segments of the thoracic aorta without visible atherosclerotic lesions. DHE fluorescence microscopy demonstrated that most of the superoxide was located in the medial layer, indicating a major contribution of vascular smooth muscle cells. Together with the finding that HO-1 is highly induced in the medial layer, our data suggest that HO-1 expression influences the nonphagocytic NADPH oxidase in vascular cells. However, it should be noted that this inhibitory effect of HO-1 is not specific for vascular NADPH oxidase, because the HO-1 product bilirubin also potently suppressed NADPH oxidase activity in neutrophil-like HL-60 cells (Figure 5).

A similar inhibitory effect of HO-1 on NADPH oxidase was also observed in the kidney. Increased oxidative stress has been identified in the kidney during ischemia reperfusion injury, chronic renal failure, hypertension, and diabetic nephropathy. Administration of antioxidants ameliorates kidney dysfunction induced by radiographic contrast agents in patients with mild renal insufficiency. Moreover, forced expression of HO-1 by pharmacological inducers or HO-1 gene transfer protects the kidney from Ang II–induced oxidative stress, apoptosis, and renal dysfunction. Taken together, we suggest that modulating NADPH oxidase activity in the kidney may be an important mechanism of the renal protective actions of HO-1.

The mechanisms by which HO-1 modulates NADPH oxidase activity are not totally clear. The protein levels of the Nox subunits in either kidney or aorta were not altered after HO-1 induction, in contrast to the findings by Taille et al in macrophages. However, an impact of HO-1 on the expression of other subunits cannot be ruled out. On the other hand, our data raise the alternative possibility that the inhibition of NADPH oxidase by HO-1 may be mediated by its product bilirubin, because we have shown that exogenous bilirubin inhibited NADPH oxidase–dependent superoxide production in isolated aorta, cultured RASMCs, and neutrophil-like HL-60 cells. These observations are consistent with previous findings in both reconstituted neutrophil NADPH oxidase and vascular endothelial cells. In RASMCs, we also found that bilirubin suppressed Ang II–induced NADPH oxidase activation, and bilirubin seemed to be a more potent inhibitor in Ang II–treated cells than in resting cells. It could be that bilirubin may interfere with agonist-induced assembly of the NADPH oxidase enzyme complex in the membrane and its subsequent activation. Moreover, in vivo hemin treatment resulted in an increase in plasma bilirubin of 4 μmol/L, which is within the range of concentration used in the in vitro experiments. These actions of bilirubin are, however, independent of ROS scavenging, because the superoxide-scavenging effect of bilirubin is weak. Indeed, the inhibition of NADPH oxidase activity by bilirubin persisted after the cells had been washed. On the other hand, whereas our results suggest that bilirubin has a pivotal role in the antioxidant effects of HO-1, we cannot exclude that other intermediate products of HO-1, such as carbon monoxide or biliverdin, may also be involved.

We also found that plasma F₂-isoprostanones, markers of lipid peroxidation, were decreased by 25% in hemin-treated animals, indicating that hemin-induced HO-1 expression was associated with reduced systemic oxidative stress. Moreover, in the presence of SnPP, hemin did not further reduce...
F₂-isoprostanes. The low level of F₂-isoprostanes in the hemin plus SnPP group, however, could indicate that the dose of SnPP used might not be sufficient to inhibit HO in vivo. However, this is unlikely, because the enzyme activity of HO in the kidney was significantly reduced by SnPP. Interestingly, we found that treatment with SnPP alone also reduced the F₂-isoprostane level, and this effect of SnPP prevented us from establishing a direct link between HO-1 expression and systemic F₂-isoprostane levels. The mechanism of this effect of SnPP remains unclear. Of note, F₂-isoprostanes are products of phospholipid peroxidation induced by free radicals, and we propose that SnPP might act as a chain-breaking antioxidant given its protoporphyrin structure. In addition, we found that the plasma nitrate/nitrite level was increased in the hemin-treated group. Although this effect may not be directly linked to improved endothelial function, given the recent findings that ROS may oxidize the cofactors of endothelial NO synthase, leading to uncoupled endothelial NO synthase.40

Antioxidant given its protoporphyrin structure.34 In addition, epidemiological studies have identified an inverse relationship between the serum bilirubin level and the risk of cardiovascular disease.44 Our findings suggest that suppression of the NADPH oxidase activity may be a mechanism involved in the antihypertensive and other cardiovascular-protective effects of HO-1 and bilirubin.

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Disclosures
None.

References


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