Increased NADPH Oxidase Activity, gp91phox Expression, and Endothelium-Dependent Vasorelaxation During Neointima Formation in Rabbits

Tamara M. Paravicini, Lerna M. Gulluyan, Gregory J. Dusting, Grant R. Drummond

Abstract—Reactive oxygen species including superoxide and hydrogen peroxide are important mediators in atherogenesis. We investigated the enzymatic source of vascular superoxide and its role in endothelium-dependent vasorelaxation during neointima formation. Silastic collars positioned around carotid arteries of rabbits for 14 days induced neointimal thickening. Using lucigenin-enhanced chemiluminescence, superoxide production was detectable in collared artery sections, but not in controls, only after inactivation of endogenous Cu2+/Zn2+-superoxide dismutase (Cu2+/Zn2+-SOD) with diethyldithiocarbamate (DETCA). Dihydroethidium staining indicated that endothelium and adventitia were the major sites of superoxide generation. Superoxide production in DETCA-treated collared arteries was enhanced further by NADPH and was inhibited by diphenyleneiodonium, suggesting NADPH oxidase was the source of the radical in collared arteries. Moreover, real-time PCR demonstrated 11-fold higher expression of the gp91phox subunit of NADPH oxidase in collared arteries than in controls. In vascular reactivity studies, endothelium-dependent vasorelaxation to acetylcholine did not differ between collared and control sections. However, treatment with DETCA reduced relaxations to acetylcholine in collared rings, but not in controls. NADPH further reduced relaxations to acetylcholine in DETCA-treated collared sections, but not in controls. NADPH further reduced relaxations to acetylcholine in DETCA-treated collared sections, but not in controls. In DETCA/NADPH-treated collared rings, sensitivity to nitroprusside, in contrast to acetylcholine, exceeded that of controls. Moreover, further treatment of such rings with exogenous Cu2+/Zn2+-SOD restored acetylcholine relaxations without altering nitroprusside responses. Thus, early neointimal lesions induced by perivascular collars are associated with elevated gp91phox expression and increased NADPH-oxidase–dependent superoxide production in endothelium and adventitia. However, endothelium-dependent vasorelaxation is largely preserved due to the actions of Cu2+/Zn2+-SOD and increased smooth muscle sensitivity to nitric oxide. (Circ Res. 2002;91:1111–1119.)

Key Words: NADPH oxidase, superoxide, gp91phox, endothelium-dependent vasorelaxation, collar-induced atherosclerosis

Reactive oxygen species (ROS) are important mediators in atherogenesis. Not only is superoxide production increased in atherosclerotic arteries from humans, rabbits, and mice, but ROS have also been shown to induce many proatherogenic cellular responses in vitro. These include inactivating endothelium-derived nitric oxide, inducing endothelial cell apoptosis, upregulating endothelial cell adhesion molecule expression, stimulating the proliferation and migration of vascular smooth muscle cells, and oxidatively modifying lipoproteins.

To our knowledge, only one study has attempted to characterize the oxidase responsible for superoxide production in atherosclerotic lesions. Warnholtz et al demonstrated that superoxide production in aortas from Watanabe heritable hyperlipidemic and cholesterol-fed rabbits was markedly higher than that in controls. The enzyme responsible for superoxide production in these atherosclerotic arteries was membrane-associated, stimulated by NADH and NADPH, and inhibited by the flavoprotein inhibitor, diphenyleneiodonium (DPI). Collectively, these observations provided evidence for the involvement of an NADPH oxidase, at least in these hypercholesterolemic models of atherosclerosis. NADPH oxidases are a family of enzymes that generate superoxide by transferring electrons from NADPH and/or NADH to molecular oxygen via flavins within their structure. NADPH oxidases are made up of at least 3 cytosolic protein subunits, p47phox, p67phox, and the G-protein, Rac, as well as a membrane-bound cytochrome reductase domain. The cytochrome domain is a heterodimeric protein comprising a 22-kDa α-subunit called p22phox as well as a larger, flavin-containing β-subunit that is required for substrate binding and electron transfer. The nature of the β-subunit appears to depend on cell type. Although gp91phox is associated with p22phox in neutrophils, endo-
thelial cells and adventitial fibroblasts, homologues of this subunit such as Nox1 or Nox4 may be important in vascular smooth muscle cells.11 It was recently found that expression of p22phox and gp91phox are elevated in human atherosclerotic lesions.12,13 Moreover, polymorphisms in the gene that encodes p22phox appear to be independently associated with increased superoxide production14 and elevated risk factors for atherosclerosis in some populations.15

Neointimal lesions displaying many characteristics of early stage human atherosclerosis can be rapidly induced in rabbits by periarterial collars.16–18 Such characteristics include infiltration of macrophages, accumulation of cholesterol esters, and deposition of collagen and fibronectin within the intima.16,17 In addition, the neointima contains smooth muscle cells that repicate in the media before migrating across the internal elastic lamina.17 Collar-induced lesions also display functional changes similar to those that occur in early human atherosclerosis including hypereosinophilia to the vasoconstrictor action of 5-hydroxytryptamine (5-HT).17,18 Importantly, the endothelial layer remains morphologically intact, although functionally impaired.18,19 Thus, although relaxations to directly acting nitrovasodilators are preserved in collared arteries, some authors have reported impaired endothelium-dependent vasorelaxations to acetylcholine,17,20,21 whereas unaltered.22,23

We set out to determine the enzymatic source of superoxide in arterial lesions induced by periarterial collars and to examine its effect on endothelium-dependent vasorelaxations. Our results provide the first evidence for a role for NADPH oxidase in superoxide production and the ensuing endothelial dysfunction in a non-hyperlipidemic model of atherosclerosis.

**Materials and Methods**

**Animals**

Male New Zealand White rabbits (3 to 4 kg) were maintained on a normal chow diet. All procedures were approved by the Institute’s Animal Ethics Committee (No. 99056).

**Collar Implantation**

Animals were anesthetized with propofol (5 mg/kg, IV) followed by ketamine/xylazine (50/10 mg/kg, IM). Left and right common carotid arteries were exposed surgically and cleared of connective tissue along a 30-mm length. Hollow, nonocclusive silastic collars (2.5 mm) were then placed around each artery and held in place at ends 1 mm) were taken from each region for morphological analysis.

**Measurement of Neointima Formation**

Ring segments (1 mm) were fixed in 4% paraformaldehyde for 4 hours at 4°C, dehydrated in ethanol, and embedded in paraffin. Transverse sections (4 μm) were stained with hematoxylin and eosin. Using a MicroComputer Imaging Device (version 3.0, Imaging Research Inc), the cross-sectional areas of the intimai and medial regions were measured in micrometers squared and expressed as an intima-media ratio (IMR) to quantify neointima formation.

**Detection of Superoxide by Lucigenin-Enhanced Chemiluminescence**

Superoxide production by control and collared carotid artery ring segments was measured using 5 μmol/L lucigenin-enhanced chemiluminescence as previously described.3

**Localization of Superoxide by Dihydroethidium**

Dihydroethidium (2 μmol/L) was used as previously described to detect superoxide in frozen sections (20 μm) of control and collared artery.2

**RNA Preparation**

Carotid artery ring segments were placed in a mortar, overlaid with liquid nitrogen, and pulverized. The resulting powder was transferred to a microcentrifuge tube containing 500 μL of RNAlater (Ambion), and total RNA was extracted according to the manufacturer’s instructions. RNA concentrations were determined spectrophotometrically by measuring absorbance at 260 nm.

**Reverse Transcription (RT) Reaction**

RNA (2 μg) was used for RT in a final reaction volume of 200 μL. The reaction mixture consisted of 1X Taqman RT buffer, 5.5 mmol/L MgCl2, 2.5 μmol/L random hexamers, 2 mmol/L deoxynucleoside triphosphates, 0.4 U/μL RNase inhibitor, and 1.25 U/μL MultiScribe Reverse Transcriptase (PE Biosystems). As a control for genomic DNA contamination in subsequent real-time PCR, 500 ng of each RNA sample was also added to parallel RT reaction mixtures that contained all of the above reagents except the Reverse Transcriptase. Reverse transcription was performed in a GeneAmp 9600 thermocycler (Perkin Elmer) using the following parameters: 10 minutes at 25°C, 30 minutes at 48°C, and 5 minutes at 95°C. Samples were stored at −20°C.

**Real-Time PCR**

Real-time PCR and the ΔΔCt method were used as previously described to examine mRNA expression of the flavin-containing NADPH oxidase subunits gp91phox, Nox1, and Nox4 relative to a “reference” sample.24 Primers and 5′-FAM–labeled fluorescent probes for gp91phox and Nox1 were designed using Primer Express software (PE Biosystems) and the published sequences for the rabbit homologues of each gene (Table). For Nox4, where a rabbit sequence has not been described, a region of high homology between the mouse and rat homologues of the gene was identified and used to design optimal primers, again with Primer Express software (PE Biosystems) and the published sequences for the rabbit homologues of each gene (Table). For Nox4, where a rabbit sequence has not been described, a region of high homology between the mouse and rat homologues of the gene was identified and used to design optimal primers, again with Primer Express software (PE Biosystems) and the published sequences for the rabbit homologues of each gene (Table). Because probe binding in real-time PCR does not tolerate a single base mismatch, SYBR Green (PE Biosystems) was used in the Nox4 PCR mixture in place of a labeled probe. Ribosomal RNA (18s) was used as the internal standard for each reaction and was detected with commercially available rodent 18s primers and 5′-VIC–labeled probes (PE Biosystems; Table).

**Assessment of Endothelial Nitric Oxide Function**

Carotid artery rings were suspended between 2 stainless steel wire hooks, one connected to an isometric force transducer (FT-03, Grass Instruments) and the other to an adjustable support. Preparations were immersed in water-jacketed organ baths containing Krebs bicarbonate buffer (pH 7.4) bubbled with 95% O2 and 5% CO2 and maintained at 37°C. Circumferential force was measured with a Powerlab running Chart software (version 3.6.3; AD Instruments). Tissues were equilibrated for 20 minutes under zero tension and a
Further 20 minutes under 2 g resting tension. Bath contents were then replaced with an isotonic, 125 mmol/L potassium physiological salt solution (KPSS) to induce a maximum contraction (KPSSmax). After washing the tissues with fresh Krebs-bicarbonate buffer, cumulative concentration-response curves to 5-HT (0.1 to 10 μmol/L) were constructed to confirm that collared vessels had undergone functional changes characteristic of atherosclerosis.18 Tissues were again washed with fresh Krebs-bicarbonate buffer and treated with one or more of the following drugs: paraquat (10 mmol/L); diethyldithiocarbamate (DETC, 3 mmol/L); NADPH (100 μmol/L); and Cu2+/Zn2+ superoxide dismutase (Cu2+/Zn2+-SOD, 600 U/mL). Note, when DETCA was used, the bathing solution was replaced with fresh Krebs-bicarbonate buffer after the 20 minutes incubation to avoid any nonspecific interactions of DETCA with divalent cations. Rings were then precontracted to 50% to 60% KPSSmax with titrated concentrations of 5-HT and relaxed with cumulatively increasing concentrations of acetycholine (0.001 to 30 μmol/L) were then precontracted to 50% to 60% KPSSmax with titrated concentrations of 5-HT and relaxed with cumulatively increasing concentrations of acetycholine (0.001 to 30 μmol/L). In some experiments, rings were again washed with fresh Krebs-bicarbonate buffer and the appropriate drug treatment(s) replaced in the organ bath. Rings were then precontracted with 5-HT and relaxed with cumulatively increasing concentrations of sodium nitroprusside (0.001 to 30 μmol/L). Cumulative responses were expressed as change in force (g), and relaxations expressed as percent relaxation of 5-HT–induced precontraction. Nonlinear regression (Prism, version 3.0) was used to determine pEC50 and maximum responses (Rmax) to 5-HT, acetylcholine (0.001 to 30 μmol/L) were then precontracted to 50% to 60% KPSSmax with titrated concentrations of 5-HT and relaxed with cumulatively increasing concentrations of acetycholine (0.001 to 30 μmol/L). In some experiments, rings were again washed with fresh Krebs-bicarbonate buffer and the appropriate drug treatment(s) replaced in the organ bath. Rings were then precontracted with 5-HT and relaxed with cumulatively increasing concentrations of sodium nitroprusside (0.001 to 30 μmol/L). Cumulative responses were expressed as change in force (g), and relaxations expressed as percent relaxation of 5-HT–induced precontraction. Nonlinear regression (Prism, version 3.0) was used to determine pEC50 and maximum responses (Rmax) to 5-HT, acetylcholine, and nitroprusside in each ring.

**Data Analysis**

All results are expressed as mean±standard error of the mean (SEM). Statistical comparisons were made by paired t tests or by 1- or 2-way repeated measures ANOVA with Bonferroni corrections where appropriate. A value of P<0.05 was considered significant.

An expanded Materials and Methods section can be found in the online data supplement available at http://www.circresaha.org.

**Results**

**Induction of Atheroma-Like Lesions by Periarterial Collars**

Carotid artery segments that had been collared for 14 days developed a substantial neointima (IMR 0.22±0.06 versus 0.01±0.01 in control arteries; n=39, P<0.05) while maintaining a morphologically intact endothelium. In contrast, paired control segments did not display any neointimal thickening (Figure 1).

**Production of Superoxide in Collared Sections**

Superoxide production could not be detected in untreated control or collared artery ring segments using lucigenin-enhanced chemiluminescence (n=4). However, after inactivation of endogenous Cu2+/Zn2+-SOD with DETCA, superoxide was detected in collared ring segments (27±9 counts/s per milligram; n=6) but not in control rings (Figure 2). Superoxide production was increased further in DETCA-treated collared rings by NADPH (156±32 counts/s per milligram; P<0.05 versus DETCA-treated alone; n=6; Figure 2). In contrast, although NADH increased superoxide in some DETCA-treated collared rings (70±24 counts/s per milligram; n=6), this effect did not reach statistical significance overall (Figure 2). Neither NADPH nor NADH had any significant effect on superoxide production in DETCA-treated control segments (n=6; Figure 2).

**Cellular Localization of Superoxide in Collared Sections**

Dihydroethidium staining of DETCA-treated control and collared segments of carotid artery revealed that superoxide production was primarily localized in the endothelial layer (n=4; Figure 3). Staining was also visible in the adventitial layer, particularly in collared arteries in a thin outer rim of cells, which were presumably invading inflammatory cells (n=4; Figure 3). Only low levels of superoxide were detected in the medial smooth muscle layer and this did not differ between control and collared sections (n=4; Figure 3). In adjacent sections of artery treated with the superoxide scavenger, tiron, fluorescence intensity, particularly in the endothelial and adventitial layers, was markedly reduced, confirming specificity for superoxide (n=4; Figure 3).

**Characterization of Enzymatic Source of Superoxide**

Superoxide production in DETCA-treated collared sections (83±33 counts/s per milligram) was reduced by the flavin antagonist and NADPH oxidase inhibitor, DPI (26±8 counts/s per milligram; n=5, P<0.05). 6-Aminonicotinamide, an inhibitor of pentose phosphate-dependent NADPH production, also appeared to attenuate superoxide production in unstimulated collared rings (27±29 counts/s per milligram; n=5), but this effect did not reach statistical significance (Figure 4). Similar to the above, DPI inhibited NADPH-stimulated superoxide production in DETCA-treated collared rings (134±29 versus 45±23 counts/s per milligram in DPI-treated
rings; n=4, P<0.05). NADPH-stimulated superoxide production was also blocked by the SOD-mimetic, tiron (14±10 counts/s per milligram; n=4, P<0.05), but not by L-NAME, an inhibitor of nitric oxide synthase, or allopurinol, an inhibitor of xanthine oxidase (Figure 4). None of the above treatments affected superoxide production in control segments (Figure 4).

NADPH Oxidase Expression

To determine whether increased NADPH oxidase activity in collared arteries was associated with upregulation of one or more NADPH oxidase isoforms, real-time PCR was used to measure mRNA expression of gp91phox, Nox1, and Nox4. In all cases, 18s was used as the internal standard. Gp91phox was detected 3.5 cycles earlier in collared samples (ΔCt, 15.2±0.3) than in control samples (ΔCt, 18.5±0.1), indicating that gp91phox is 11-fold more highly expressed in collared arteries (n=3, P<0.05; Figure 5). In contrast, Nox4 expression did not differ between control (ΔCt, 19.8±0.0) and collared (ΔCt, 19.7±0.2) arteries (Figure 5). We were unable to detect Nox1 message in either collared or control samples, even when 50 ng of cDNA template was used.

Contractile Responses in Collared Sections

In all experiments, rings were initially contracted with KPSS followed by cumulatively increasing concentrations of 5-HT to confirm that the collar had induced functional changes as previously observed. In contrast, both the sensitivity and maximum contractions to 5-HT were enhanced in collared rings (pEC50, 7.3±0.1; Rmax, 5.0±0.3 g) compared with controls (pEC50, 6.4±0.1; Rmax, 3.2±0.1 g; n=24 from 10 animals; P<0.05).

Endothelium-Dependent Vasorelaxations Associated With Increased Superoxide Levels

Acetylcholine caused concentration-dependent vasorelaxations in precontracted control rings (pEC50, 7.6±0.1; Rmax, 95±1%; n=5; Figure 6) that were not different, in these studies, from those in collared rings (pEC50, 7.4±0.2; Rmax, 102±1%; n=5; Figure 6). However, although DETCA treatment had no effect on responses to acetylcholine in control segments, it caused a 6-fold reduction in sensitivity (pEC50, 7.6±0.1; Rmax, 95±1%; n=5; Figure 6).
6.8±0.2; n=5, P<0.05) without altering maximum relaxations (R\textsubscript{max}, 94±3%) to acetylcholine in collared rings (Figure 6). Additional treatment with NADPH attenuated further the maximum relaxations to acetylcholine in collared rings (R\textsubscript{max}, 83±7%; n=5, P<0.05) but still had no effect in control rings (Figure 6).

Like DETCA and NADPH, an exogenous superoxide-generating compound, paraquat (10 mmol/L), significantly reduced both sensitivity (pEC\textsubscript{50}, 6.0±0.1 versus 7.2±0.2 in controls; n=7, P<0.001) and maximum relaxations (R\textsubscript{max}, 73±9% versus 94±2% in controls; n=7, P<0.05) to acetylcholine in noncollared ring segments (Figure 6).

To confirm that the DETCA/NADPH-induced attenuation of acetylcholine responses in collared rings was due to increased superoxide, in a separate series of experiments, we examined the effects of exogenous Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD. In collared rings, treatment with Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD significantly reduced maximum relaxations to acetylcholine (R\textsubscript{max}, 80±3% versus 94±2% in controls; n=7, P<0.05). These findings suggest that superoxide generation by the NADPH oxidase is a key factor in the impaired vasodilation in atherosclerotic arteries.
lared rings cotreated with DETCA and NADPH, acetyloclione caused concentration-dependent relaxations (pEC\textsubscript{50}, 6.7±0.1; R\textsubscript{max}, 77±10\%) that were of lower sensitivity and R\textsubscript{max} than those obtained in similarly treated control rings (pEC\textsubscript{50}, 7.4±0.1; R\textsubscript{max}, 92±2\%; n=6, P<0.05 for both values; Figure 7). However, additional treatment of DETCA/NADPH-treated collared rings with native Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD significantly increased both the pEC\textsubscript{50} and R\textsubscript{max} to acetyloclione (pEC\textsubscript{50}, 7.3±0.1; R\textsubscript{max}, 95±4\%) such that the response was not significantly different from that in control rings (Figure 7). Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD had no effect on relaxations to acetyloclione in DETCA/NADPH-treated control rings (Figure 7).

In marked contrast to the impaired responses to acetyloclione, relaxations to the nitric oxide donor, sodium nitroprusside, in DETCA/NADPH-treated collared rings (pEC\textsubscript{50}, 7.8±0.1; n=5) were located to the left of similarly treated control rings (pEC\textsubscript{50}, 7.4±0.1; n=5, P<0.05), although there was no difference in maxima. Unlike responses to acetyloclione, relaxations to nitroprusside in control and collared rings were not altered by exogenous Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD (Figure 7).

Discussion

The major finding in this study is that neointimal thickening induced by periartrial collars in rabbits is accompanied by increased superoxide production, most likely derived from upregulation of a gp91phox-containing NADPH oxidase in the endothelial and adventitial layers of the artery wall. Our conclusion that superoxide is elevated in collared arteries, and that this has functional consequences in terms of reduced bioavailability of nitric oxide, is supported by functional studies performed after inactivation of endogenous Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD by DETCA. This study thus exposes 2 mechanisms that compensate for increased superoxide production in the artery wall: endogenous Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD, which disposes of excess superoxide production, as well as a compensatory increase in the sensitivity of the underlying smooth muscle to nitric oxide. This is the first study to implicate a role for NADPH oxidase in elevated superoxide production in a non-hyperlipidemic model of early stage atherosclerosis.

To measure superoxide production in carotid artery segments, we utilized the chemiluminescent probe, lucigenin. Superoxide was undetectable in control arteries even after inactivating endogenous Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-SOD with DETCA. In contrast, DETCA markedly increased superoxide production in collared arteries, suggesting that Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-containing isoform(s) of SOD may play an important protective role in atherosclerotic arteries. This is despite the fact that total SOD activity in rabbit carotid arteries was reduced by 50% after 14 days with periartrial collars and activity of extracellular SOD (the most abundant Cu\textsuperscript{2+}/Zn\textsuperscript{2+}-containing isoform of SOD in vascular tissue) is known to be suppressed in arteries from patients with coronary artery disease. In the presence of SOD activity, hydrogen peroxide and its myeloperoxidase and Fenton-derived products, hypochlorite and hydroxyl radicals, could themselves promote atherogenesis via several mechanisms, including upregulation of endothelial cell adhesion molecule expression, vascular smooth muscle cell proliferation and migration, and oxidative modification of lipoproteins. However, the status of hydrogen peroxide–metabolizing pathways such as catalase and glutathione peroxidase in periartrial collar-induced neointima formation, nor indeed in other models of atherosclerosis, remains unclear.

In addition to the quantitative chemiluminescence data, we also sought to localize superoxide production in DETCA-treated collared arteries. Staining of arterial sections with dihydroethidium clearly demonstrated that the endothelium was the primary source of superoxide in collared arteries with lower levels of staining evident in the outer layers of the adventitia. Because the endothelium is the major site for production of vasoprotective nitric oxide, generation of su-

Figure 5. Messenger RNA expression of NADPH oxidase subunits gp91phox (A) and Nox4 (B) in control (open bars) and collared (filled bars) carotid artery rings. Total RNA was extracted from control and collared artery ring segments and reverse transcribed. cDNA (5 to 10 ng) was then used in real-time PCR to examine expression of gp91phox and Nox4 relative to that of the housekeeping gene 18s. A, Left, Plots of FAM (gp91phox); Top) and VIC (18s; Bottom)-dependent fluorescence intensities vs PCR cycle number from a single control and paired collared artery cDNA sample (run in triplicate). As a control for genomic DNA contamination, real-time PCR was also performed using, as a template, samples that had not been reverse transcribed (–RT). Values (mean±SEM from 3 experiments) in (A, Right) and (B) are expressed relative to a reference sample. *P<0.05 vs control rings. Nox1 was not detected in either control or collared samples (data not shown).
peroxide in this location in the early stages of atherosclerosis has important implications for subsequent lesion development. Not only would superoxide react with and reduce the bioavailability and antiatherosclerotic actions of nitric oxide, but the product of this reaction, peroxynitrite, may itself directly contribute to atherogenesis. In addition to oxidizing lipoproteins, modifying protein function and inducing endothelial cell apoptosis, peroxynitrite may further compromise endothelial function in atherosclerosis by oxidizing tetrahydrobiopterin, an essential cofactor for nitric oxide synthase.3

To investigate the enzymatic source of superoxide in collared arteries we first excluded nitric oxide synthase and xanthine oxidase using the inhibitors L-NAME and allopurinol, respectively. We also demonstrated that the oxidase utilized exogenous NADPH in preference to NADH as an electron donor substrate and that oxidase activity was inhibited by the flavin antagonist and NADPH oxidase inhibitor, diphenyleneiodonium. Taken together, these results suggest that an NADPH oxidase is the most likely source of superoxide in these neointimal lesions. To determine the isoform(s) of NADPH oxidase involved, we examined expression of gp91phox, Nox1, and Nox4. Within the vascular wall, gp91phox is thought to be associated with endothelial isoforms of NADPH oxidase,27 whereas Nox1 appears to be involved in superoxide production by vascular smooth muscle cells.10,11 Nox4 is highly expressed in all vascular cell types but its role in superoxide production in these cells remains to be determined.11,13 Using real-time PCR, we have now demonstrated that expression of gp91phox is markedly increased in collared arteries compared with controls. In contrast, Nox1 expression was not detectable in either tissue and, although Nox4 was detectable in carotid arteries, its expression was not altered by the collar. These findings are in agreement with those from a recent study on human atherosclerotic arteries where it was shown that gp91phox expression is strongly correlated with lesion severity.13 In contrast, no such correlation was evident between Nox4 expression and disease stage.13

Sequence analysis of gp91phox family members across a number of species reveals the presence of a highly conserved canonical nucleotide binding sequence Gly-Xaa-Gly-Xaa-Pro.28 This is followed by Phe or Tyr, which is characteristic of flavoproteins that bind NADPH in preference to NADH28 and is thus consistent with our findings that exog-
enous NADPH is more efficacious than NADH at driving superoxide production in collared arteries. To examine the role of endogenous NADPH in superoxide production, we used the pentose phosphate pathway inhibitor, 6-amino-nicotinamide. The pentose phosphate pathway is one of two major metabolic pathways responsible for maintaining NADP(H) in its reduced form in mammalian cells. Although 6-amino-nicotinamide appeared to reduce basal superoxide production in collared arteries (ie, 50% reduction), this effect just failed to reach statistical significance. This may be because even after inhibition of the pentose phosphate pathway, the intracellular concentration of NADPH is preserved by the other major pathway of NADPH regeneration, namely the malic enzyme-catalyzed conversion of malate to pyruvate. In support of this, Gupte et al recently showed that 6-amino-nicotamide only reduced intracellular NADPH levels by 30% to 35% in isolated bovine pulmonary arteries.

Increased production of oxyradicals has been shown to compromise acetylcholine-induced relaxations in many isolated blood vessels. Indeed, in the present study, we confirmed that increased superoxide production is capable of attenuating endothelial function in rabbit carotid arteries by demonstrating that paraquat, a known generator of intracellular superoxide, reduced relaxations to acetylcholine. Surprisingly, in contrast to our earlier studies with a shorter period of neointima formation, relaxations in collared arteries were not different from those in control arteries, despite the increase in NADPH oxidase activity in these arteries. Only after inactivation of endogenous CuZn-SOD in collared rings were superoxide levels sufficient to blunt endothelium-dependent vasorelaxation to acetylcholine. These findings again highlight the importance of CuZn-containing isoforms of SOD that “dispose” of the increased superoxide produced by NADPH oxidase, thereby maintaining normal endothelium-dependent vasodilator function. It is also important to note that at the level of the contractile vascular smooth muscle, the sensitivity (presumably of the soluble guanylate cyclase) to nitric oxide appears to be increased in collared sections, because vasorelaxations to the nitric oxide donor nitroprusside are enhanced. Therefore, at this stage of pathology in this model, two mechanisms appear to compensate for the increase in NADPH oxidase activity, such that the vasodilator function of nitric oxide is preserved. It is less likely, however, given that endothelial dysfunction is clearly evident in atherogenesis in human patients and many animal models, that these mechanisms are always able to compensate adequately for the compromised bioavailability of nitric oxide. Also, although vasodilator function may be partially protected, other antiatherogenic actions of endothelium-derived nitric oxide may not be as well preserved throughout all stages of atherogenesis.

Supplementation with exogenous CuZn-SOD completely restored responses to acetylcholine after DETCA/NADPH-treatment in collared arteries, confirming that the effects of DETCA and NADPH were attributable to increased superoxide generation. In contrast, the increased sensitivity to nitroprusside in collared arteries was not reversed by exogenous CuZn-SOD, indicating that this compensation of the vascular smooth muscle for reduced nitric oxide bioavailability was not an event that could be rapidly reversed by restoring the nitric oxide/superoxide balance.

In conclusion, we have now demonstrated increased gp91phox expression associated with elevated endothelial and adventitial NADPH oxidase–dependent superoxide production in a normocholesterolemic model of vascular remod-
eling. Increased superoxide caused impairment of endotheli-um-dependent vasorelaxation that was revealed after inhibition of endogenous Cu²⁺/Zn²⁺-SOD. Whether increased dismutation of superoxide might protect against atherogene-sis awaits further studies into the status of hydrogen peroxide metabolizing pathways in atherosclerosis. Whatever the outcome of these studies, targeting superoxide production at its enzymatic source may be a more effective approach than conventional antioxidants for preventing arterial damage by reactive oxygen species.

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