Decreased Atherosclerotic Lesion Formation in Human Serum Paraoxonase Transgenic Mice

Aaron Tward, MA; Yu-Rong Xia, BS; Xu-Ping Wang, MD; Yi-Shou Shi, BS; Christina Park, BS; Lawrence W. Castellani, PhD; Aldons J. Lusis, PhD; Diana M. Shih, PhD

Background**—**Serum paraoxonase (PON1), an enzyme carried on HDL, inhibits LDL oxidation, and in human population studies, low PON1 activity is associated with atherosclerosis. In addition, PON1 knockout mice are more susceptible to lipoprotein oxidation and atherosclerosis. To evaluate whether PON1 protects against atherosclerosis and lipid oxidation in a dose-dependent manner, we generated and studied human PON1 transgenic mice.

Methods and Results**—**Human PON1 transgenic mice were produced by using bacterial artificial chromosome genomic clones. The mice had 2- to 4-fold increased plasma PON1 levels, but plasma cholesterol levels were unchanged. Atherosclerotic lesions were significantly reduced in the transgenic mice when both dietary and apoE-null mouse models were used. HDL isolated from the transgenic mice also protected against LDL oxidation more effectively.

Conclusions**—**Our results indicate that PON1 protects against atherosclerosis in a dose-dependent manner and suggest that it may be a potential target for developing therapeutic agents for the treatment of cardiovascular disease. **(*Circulation*. 2002;106:484-490.)**

Key Words: antioxidants ■ lipoproteins ■ free radicals ■ atherosclerosis ■ genes

Mounting evidence points to LDL oxidation as an important etiologic agent of atherosclerosis.[1–3] LDL is believed to exit the lumen of arteries and become trapped in the subendothelial space, perhaps by the binding of apoB-100 to intimal proteoglycans. Once trapped, LDL may become oxidized directly by cellular byproducts of respiration or enzymatically by lipoxygenases, myeloperoxidase, NADPH oxidase, cytochrome P-450, and others.[3,4] In in vitro assays, this minimally modified LDL is capable of inducing endothelial expression of adhesion molecules, chemokines, and cytokines. This evidence points to a mechanism whereby LDL oxidation is responsible in part for monocyte/macrophage recruitment and differentiation and, hence, the initiation of atherogenesis.

Substantial epidemiological evidence points to an inverse correlation between HDL levels and coronary artery disease.[5] One plausible hypothesis explaining this phenomenon is based on the idea that HDL can exert a direct antiatherogenic effect at least in part through preventing LDL oxidation.[1–3] Serum paraoxonase (PON1) is a 45-kDa glycoprotein that is expressed in the liver and has been found to be associated with HDL particles in the blood.[6,7] PON1 was initially identified for its ability to hydrolyze organophosphate insecticides.[8] More recently, PON1 has been shown to prevent LDL oxidation in vitro,[9,10] and decreased levels of PON1 are associated with an increased risk of cardiovascular disease.[10–12] In studies with PON1 knockout (KO) mice, PON1 has been shown to be both necessary and sufficient for the in vitro protective effects of HDL on LDL oxidation and monocyte transmigration.[13] Furthermore, when both dietary and apoE-null models were used, PON1 KO mice exhibited an ≈2-fold increase in atherosclerosis.[13,14]

The present study aims to provide additional in vivo evidence showing that PON1 protects against atherosclerosis. In particular, we have addressed whether in an in vivo setting PON1 influences atherosclerosis in a dose-dependent manner.

Methods

Cloning and Microinjection of Human *PON1* Gene

A clone of the human *PON1* gene in a bacterial artificial chromosome vector (GenBank No. AC004022) was purchased from Genome Systems. Polymerase chain reaction (PCR) and restriction enzyme digestion confirmed that this clone contained leucine and glutamine at codons 55 and 192, respectively. This clone, designated pPON1, was purified by CsCl gradient centrifugation. The pPON1 bacterial artificial chromosome DNA was digested with *Pme*I and then run out on a pulse field gel to separate a 45-kb DNA fragment containing the human *PON1* gene from the rest of the plasmid. The 45-kb DNA fragment was isolated from the gel, diluted to a concentration of 0.5 μg/mL, and microinjected into fertilized C57BL/6J (B6) mouse eggs (Jackson Laboratories, Bar Harbor, Me) to produce transgenic (Tg) mice.

Received March 15, 2002; revision received May 4, 2002; accepted May 6, 2002.

From the Department of Medicine (A.T., Y.-R.X., X.-P.W., Y.-S.S., C.P., L.W.C., A.J.L., D.M.S.), the Department of Microbiology, Immunology, and Molecular Genetics (A.T., A.J.L.), and the Department of Human Genetics (A.J.L.), University of California, Los Angeles. A. Tward is now at the University of California, San Francisco.

Correspondence to Dr Diana M. Shih, Division of Cardiology, Department of Medicine, University of California, Los Angeles, 47-123 CHS, UCLA, Los Angeles, CA 90095-1679. E-mail dshih@mednet.ucla.edu

Circulation is available at http://www.circulationaha.org

DOI: 10.1161/01.CIR.0000023623.87083.4F

Mice, Diets, and Atherosclerotic Lesion Analysis

Mice on the B6 background were maintained either on a 6% fat chow diet or, in the case of atherosclerotic lesion analysis, on a high fat diet (Teklad) containing 15.75% fat, 1.25% cholesterol, and 0.5% sodium cholate for 15 weeks. PON1 Tg mice on the B6 background were also backcrossed twice with the apoE KO mice on the B6 background (The Jackson Laboratory, Bar Harbor, Me) to obtain PON1 Tg/apoE KO mice and apoE KO littermates. These were maintained on a 6% fat chow diet. Lesions were analyzed as described.[14]

Southern Blot and PCR Analyses

A ^{32}P-labeled human *PON1* cDNA clone[6] was used as a probe for Southern hybridization, and bands were visualized and quantified by using a PhosphorImager 445SI (Molecular Dynamics). For routine identification of PON1 Tg mice, PCR analysis was performed with the use of the primers 5′-GCTTGATTTTTCTCCTCCAT-3′ and 5′-ATCTGTGAATGTGCTAATCC-3′, yielding a 194-bp product.

Northern Blot and Quantitative RT-PCR Analyses

Total RNA was subjected to Northern blot analysis as described.[14] For reverse transcription (RT)-PCR analysis, first-strand cDNAs were synthesized with the use of 2 μg total RNA isolated from the thoracic portion of the aorta and by use of the ThermoScript RT-PCR system (Invitrogen). Quantitative PCR was then performed with the use of the SYBR Green Jump Start Taq Ready mix (Sigma-Aldrich) in a PRISM 7700 Sequence Detector (Perkin-Elmer Applied Biosystems). The ratio of monocyte chemoattractant protein-1 (MCP-1) cDNA level relative to the vascular smooth muscle α-actin (Acta2) cDNA level of each sample was determined. The primers used for MCP-1 cDNA synthesis were 5′-CAGCCAGATGCAGTTAACGCC-3′ and 5′-TAGGGCAGATGCAGTTTTAAATAA-3′. The primers used for Acta2 cDNA synthesis were 5′-TCCGACACTGCTGACAGAGGC-3′ and 5′-CCTCATAGATAG GCACGTTGTGA-3′. The PCR conditions were as follows: 95°C for 3 minutes, 40 cycles of 95°C for 15 seconds and 68°C for 2 minutes, and 4°C hold.

Assays and LDL Oxidation

Mice were fasted for 16 hours before bleeding. Plasma lipids were determined by enzymatic colorimetric assays.[14] Plasma PON1 and arylesterase activity assays and immunoblotting of human PON1 were performed as described.[13] Plasma glucose levels were determined by using the glucose (Trinder) 100 kit (Sigma-Aldrich). Mouse HDL was isolated in the absence of EDTA by ultracentrifugation as described.[14] Human LDL was isolated by ultracentrifugation as described.[14] For the LDL oxidation assay, human LDL (1 mg/mL in PBS) was incubated with 5 μmol/L $CuSO_4$, with or without the presence of 0.25 mg/mL or 0.5 mg/mL mouse HDL, for 3 or 6 hours at 37°C. After the incubation, BHT was added to a final concentration of 20 μmol/L to stop the reaction. Lipid hydroperoxide contents of samples were then determined by use of the Fox assay.[15]

Statistical Analyses

The Student *t* test was used for analyzing all experimental data except for LDL oxidation, for which ANOVA and Fisher's protected least significant difference (PLSD) test were used.

Results

Human PON1 Tg Mice

A 45-kb fragment containing the intact human *PON1* gene with 10 kb of 5′-flanking and 10 kb of 3′-flanking sequences (Figure 1A) was used for the production of Tg mice. One Tg mouse line, designated PON1 Tg, carried ≈3 copies of the transgene, as determined by Southern blot analysis (data not shown). Tg mice were healthy and had normal weight, and the transgene was transmitted in a mendelian fashion. The PON1 transgene was maintained at a hemizygous state throughout the study so that insertional mutagenesis of the mouse genome was unlikely to contribute to the observed phenotypes, and studies with a separate line gave similar results (data not shown).

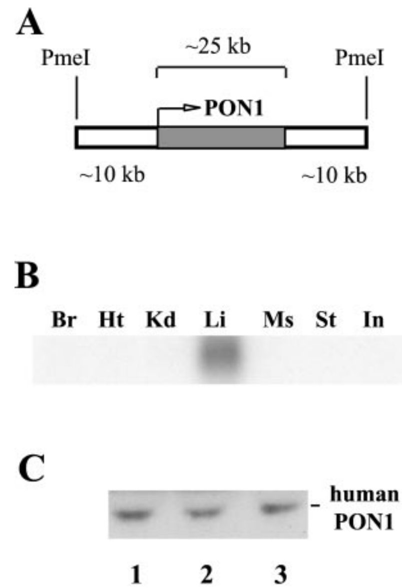

Figure 1. Construction of human PON1 Tg mice. A, A 45-kb human genomic DNA fragment, PON1, containing *PON1* structural gene (shaded bar) and flanking sequences (open bar). B, Tissue expression pattern of human *PON1* transgene. Total RNA (10 μg) isolated from various organs including brain (Br), heart (Ht), kidney (Kd), liver (Li), skeletal muscle (Ms), stomach (St), and intestine (In) of PON1 Tg mice was subjected to Northern blot analysis with use of ^{32}P-labeled human *PON1* cDNA[6] fragment as probe. C, Presence of human PON1 protein in PON1 Tg mice. Plasma samples (1 μL) from PON1 Tg (lanes 1 to 3) and wild-type mice (data not shown) were subjected to immunoblotting analysis with use of anti-human PON1 antibody.

Northern blot analysis revealed that the transgene was expressed primarily in the liver (Figure 1B), exhibiting the same expression pattern as the endogenous mouse *Pon1* gene. Western blot analysis also confirmed the presence of human PON1 protein in the plasma of Tg mice (Figure 1C). By use of the arylesterase activity assay, plasma PON1 activities of the PON1 Tg mice on chow and high fat diets were 616 and 471 $mOD_{270} \cdot min^{-1} \cdot \mu L^{-1}$, respectively, whereas plasma PON1 activities of the wild-type littermates on chow and high fat diets were 280 and 124 $mOD_{270} \cdot min^{-1} \cdot \mu L^{-1}$, respectively ($mOD_{270}$=absorbance [in milli-optical density] at wavelength 270 nm). Therefore, high fat diet feeding reduced plasma total PON1 (arylesterase) activities of the PON1 Tg and wild-type mice by 24% and 56%, respectively. Thus, when mice were maintained on a chow or a high fat diet, plasma PON1 (arylesterase) activities of the PON1 Tg mice were 2.2- and 3.8-fold higher, respectively, than those of the wild-type littermates on the same diet (Figure 2A and 2B). Hepatic mouse and human mRNA levels were also examined by Northern blot analysis in mice fed the 2 diets. Although expression of the mouse mRNA was decreased >50% in response to the high fat diet, expression of the human mRNA was not decreased by the same diet (Figure 2C).

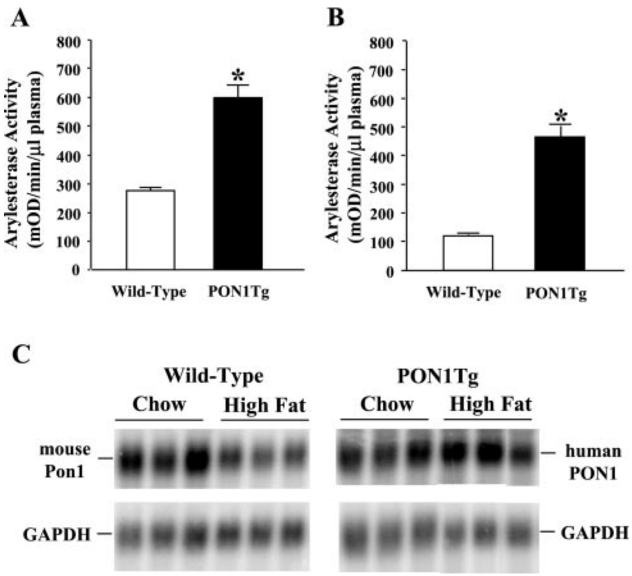

Figure 2. Plasma PON1 activities and hepatic PON1 mRNA expression of human PON1 Tg and wild-type mice. A and B, Plasma PON1 activities of wild-type (open bars) and PON1 Tg (solid bars) mice, fed a low fat chow diet (A) or a high fat atherogenic diet for 15 weeks (B), were determined by the arylesterase activity assay. Values shown are mean±SEM obtained from >10 mice from each genotype group. *$P<0.0001$ for PON1 Tg vs wild-type mice. C, Liver RNA samples (20 μg) from wild-type (left) or Tg (right) mice fed chow or high fat diet for 15 weeks were subjected to Northern blot analysis with use of probes for mouse Pon1 (upper left) or human PON1 (upper right). To standardize for loading, a mouse GAPDH cDNA probe was later used to hybridize the same filters (bottom). Hybridized bands were then quantified by PhosphorImager (see Methods).

Atherosclerotic Lesion Formation on B6 Background

Atherosclerotic lesion formation was examined in the PON1 Tg and wild-type littermates on the B6 background that were fed a high fat diet for 15 weeks. Compared with the female non-Tg littermates, the female Tg mice exhibited a 60% decrease in atherosclerotic lesion size ($P=0.13$, Figure 3A). The lack of a statistically significant result in the female group likely represents an effect of sample size. Compared with the male non-Tg littermates, the male Tg mice, on the other hand, exhibited a statistically significant 54% reduction in lesion size ($P=0.001$, Figure 3B). When data from the female and male mice were combined, the PON1 Tg mice, compared with the wild-type littermates, exhibited a statistically significant (57%) decrease in atherosclerotic lesion size ($P=0.01$, Figure 3C). Both the male and female PON1 Tg mice, compared with their wild-type littermates, exhibited similar plasma total cholesterol, VLDL/LDL cholesterol, HDL cholesterol, triglyceride, and glucose levels when they were maintained on either the chow or high fat diet (Table 1).

Atherosclerotic Lesion Formation on ApoE KO Background

The PON1 Tg mice were crossed onto the apoE KO genetic background for the study of advanced atherogenesis. When fed a chow diet, the PON1 Tg/apoE KO mice, compared with their apoE KO littermates, exhibited 2.5-fold higher plasma PON1 (arylesterase) activities (Table 2), whereas plasma total cholesterol, HDL cholesterol, VLDL/LDL cholesterol, triglyceride, and glucose levels were the same between the 2 groups (Table 2). Atherosclerotic lesion sizes of PON1 Tg/apoE KO mice at 6.5 months of age, on a chow diet, were 22% smaller than those of their apoE KO littermates ($P=0.01$) (Figure 4A). Aortic MCP-1 expression was also reduced by 44% in the PON1 Tg/apoE KO mice compared with their apoE KO littermates ($P=0.05$) (Figure 4B).

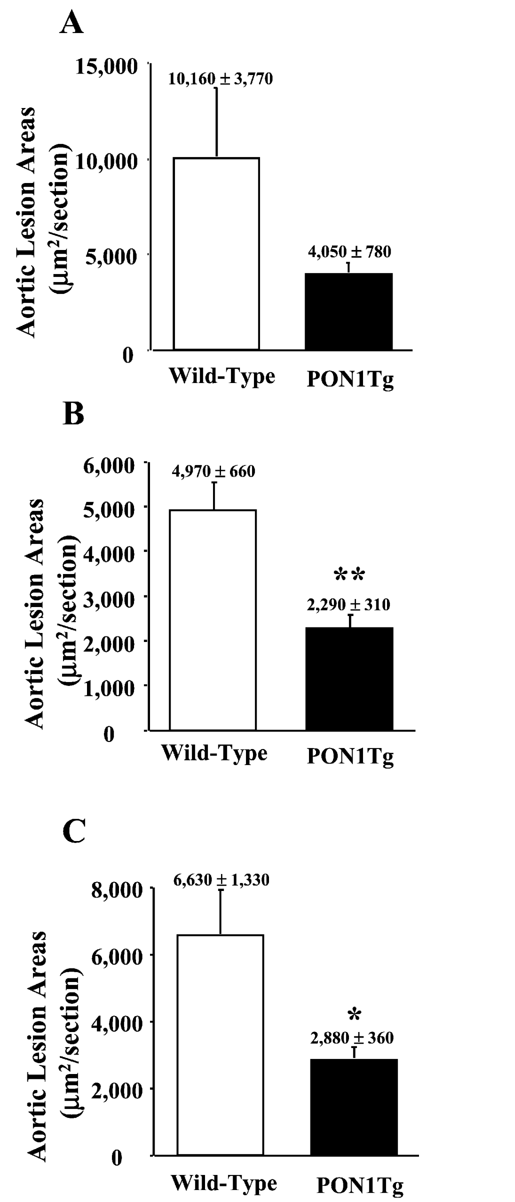

Figure 3. Decreased atherosclerotic lesion formation in PON1 Tg mice on C57BL/6J mouse background. Atherosclerotic lesions at aortic root were quantified in female wild-type (open bar, n=8) and PON1 Tg (solid bar, n=8) mice (A) or male wild-type (n=17) and PON1 Tg (n=16) mice (B) fed atherogenic diets for 15 weeks. Combined data from panels A and B are shown in panel C. Values shown are mean±SEM. *$P=0.01$ and **$P=0.001$ for PON1 Tg mice vs wild-type mice.

TABLE 1. Plasma Lipid and Glucose Levels of PON1 Tg and Wild-Type Mice Fed Chow or High-Fat Diet

Mice	Sample Size, n	Total Cholesterol, mg/dL	VLDL/LDL Cholesterol, mg/dL	HDL Cholesterol, mg/dL	Triglycerides, mg/dL	Glucose, mg/dL
Female, chow diet						
Wild type	15	97±4	19±3	77±2	30±6	100±7
PON1 Tg	14	90±4	18±3	72±2	22±8	108±3
Male, chow diet						
Wild type	19	105±2	19±2	86±2	42±6	115±4
PON1 Tg	23	107±2	18±1	88±1	35±3	111±4
Female, high-fat diet						
Wild type	13	277±19	219±20	58±6	5±1	106±5
PON1 Tg	10	308±31	253±34	56±6	5±1	106±7
Male, high-fat diet						
Wild type	19	320±17	249±19	71±3	6±1	124±5
PON1 Tg	21	318±16	243±18	75±3	8±1	126±5

Data are mean±SEM.

In Vitro Oxidation of LDL

Previously, we observed that PON1-deficient HDL lacked the ability to prevent LDL oxidation in a cell culture system of the arterial wall.[13] In the present study, we examined the ability of HDLs isolated from the human PON1 Tg mice and wild-type mice on the B6 background as well as on the apoE KO mouse background to prevent LDL oxidation induced by copper in vitro. For HDL isolated from mice on the B6 background, we found that the PON1 Tg HDL, compared with the wild-type HDL, exhibited 3.2-fold higher arylesterase activity (152 000 versus 48 000 mOD $\cdot$ min^{-1} $\cdot$ mg protein^{-1}). At a dose of 0.25 mg HDL/mL, compared with the LDL plus wild-type HDL group, the LDL plus PON1 Tg HDL group exhibited statistically significant 33% ($P<0.01$, Fisher's PLSD) and 13% ($P<0.01$) decreases in lipid hydroperoxide levels after 3 and 6 hours of incubation, respectively (Figure 5A). At a higher dose of 0.5 mg HDL/mL, compared with the LDL plus wild-type HDL group, the LDL plus PON1 Tg HDL group exhibited statistically significant 62% ($P<0.01$, Fisher's PLSD) and 19% ($P<0.0001$) reduction in lipid hydroperoxide levels after 3 and 6 hours of incubation, respectively (Figure 5B). Thus, PON1 Tg HDL prevents LDL oxidation more effectively than does the wild-type HDL.

We also examined HDLs isolated from mice on the apoE KO background for their ability to protect against LDL oxidation. We found that the PON1 Tg/apoE KO HDLs, compared with the apoE KO HDLs, exhibited 3.7-fold higher arylesterase activity (139 000 versus 37 000 mOD $\cdot$ min^{-1} $\cdot$ mg protein^{-1}). At a dose of 0.25 mg HDL/mL and after 3 hours of incubation, the LDL plus PON1 Tg/apoE KO HDL group, compared with the LDL plus apoE KO HDL group, exhibited a significant 15% ($P<0.001$, Fisher's PLSD) decrease in lipid hydroperoxide level (Figure 6A). After 6 hours of incubation and at the same dose of 0.25 mg HDL/mL, compared with the LDL group, neither the LDL plus PON1 Tg/apoE KO HDL group nor the LDL plus apoE KO HDL group exhibited any significant reduction in lipid hydroperoxide level (Figure 6A). At a higher dose of 0.5 mg HDL/mL, the LDL plus PON1 Tg/apoE KO HDL group, compared with the LDL plus apoE KO HDL group, exhibited statistically significant 21% ($P<0.0001$, Fisher's PLSD) and 14% ($P<0.01$) reduction in lipid hydroperoxide levels after 3 and 6 hours of incubation, respectively (Figure 6B). Thus, on the apoE KO mouse background, PON1 Tg HDL was also more effective in preventing LDL oxidation than was wild-type HDL.

Discussion

Both biochemical[1–3] and epidemiological[16–19] studies suggest that LDL oxidation plays a major role in the development of atherosclerosis. However, human clinical trials and animal studies that used antioxidant supplementation to treat cardiovascular disease have been inconclusive.[20–22] Alternative targets for the prevention and/or treatment of atherosclerosis

TABLE 2. Plasma Arylesterase Activity, Glucose, and Lipid Levels of PON1 Tg/ApoE KO Mice and ApoE KO Mice Fed a Chow Diet

Mice	Sample Size, n	Arylesterase Activity, $mOD_{270} \cdot min^{-1} \cdot \mu L$ Plasma^{-1}	Total Cholesterol, mg/dL	VLDL/LDL Cholesterol, mg/dL	HDL Cholesterol, mg/dL	Triglycerides, mg/dL	Glucose, mg/dL
ApoE KO	18	247±13	486±47	461±48	25±3	57±4	159±16
PON1 Tg/ApoE KO	18	610±42*	472±24	445±23	27±2	56±5	144±11

Data are mean±SEM.

*$P<0.0001$ vs corresponding value for apoE KO mice.

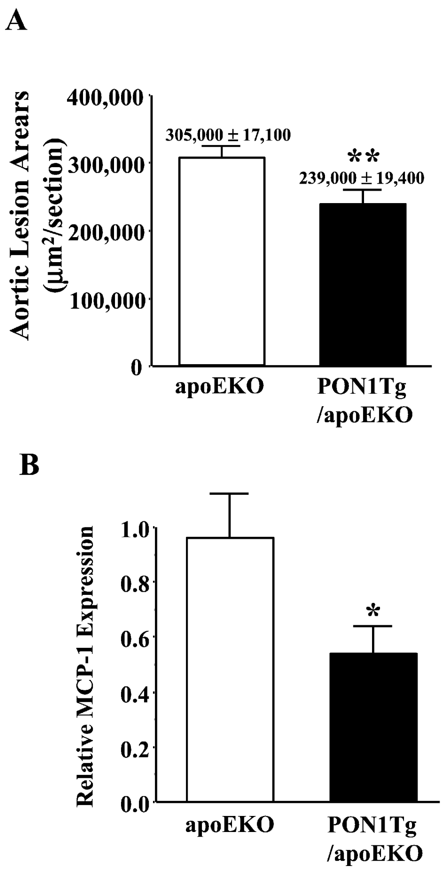

Figure 4. Decreased atherosclerotic lesion formation and MCP-1 induction in PON1 Tg mice on apoE KO mouse background. A, Aortic atherosclerotic lesions were quantified in 6.5-month-old apoE KO mice (open bar, n=21) and PON1 Tg/apoE KO mice (solid bar, n=18) maintained on chow diets. B, MCP-1 expression was examined in aortas of 9 apoE KO and 8 PON1 Tg/apoE KO mice collected in panel A by quantitative RT-PCR. Experiments were repeated 2 times with similar results. Values shown are mean±SEM of each group. *$P<0.05$ and **$P=0.001$ for PON1 Tg/apoE KO mice vs apoE KO mice.

are antioxidative enzymes on HDL, such as PON1. We have previously shown that mice lacking PON1 had increased atherogenesis,[13,14] which is consistent with predictions from in vitro studies. To determine whether high levels of PON1 can protect against LDL oxidation and decrease atherosclerosis in vivo, we have generated and characterized human PON1 Tg mice. Our results, indicating protection against both early and late stages of atherogenesis, are significant in that they demonstrate a dose-dependent effect of PON1. Hence, normal levels of PON1 are limiting with respect to their antiatherosclerotic activity. The present study is also the first to demonstrate that the human PON1 protein exhibits antioxidative and antiatherogenic functions in vivo.

We observed that the human *PON1* transgene was expressed in a liver-specific manner (Figure 1), similar to the expression pattern of the endogenous mouse *Pon1* gene, suggesting that the transgene constructs contain the necessary *cis*-regulating elements for liver-specific expression. Interestingly, expression of the human PON1 mRNA, unlike the endogenous mouse Pon1 mRNA, was not decreased by the high fat diet (Figure 2C). It is unclear whether this represents a true difference between human and mouse regulation of PON1 or if it is simply due to the construct that we used. On the basis of Northern blot analysis (Figure 2C), we conclude that the high fat diet–induced reduction of plasma total PON1 activities in the PON1 Tg and wild-type mice (Figure 2B versus 2A) is probably caused by the decreased mouse Pon1 mRNA levels.

We observed that HDL isolated from the PON1 Tg mice, compared with the wild-type HDL, exhibited ≈3-fold higher PON1 activity and was more effective at protecting against LDL oxidation (Figures 5 and 6). Several antioxidative functions of PON1 have been elucidated and include a phospholipase A_2–like activity that hydrolyzes biologically active oxidized phospholipids (such as phosphatidylcholine

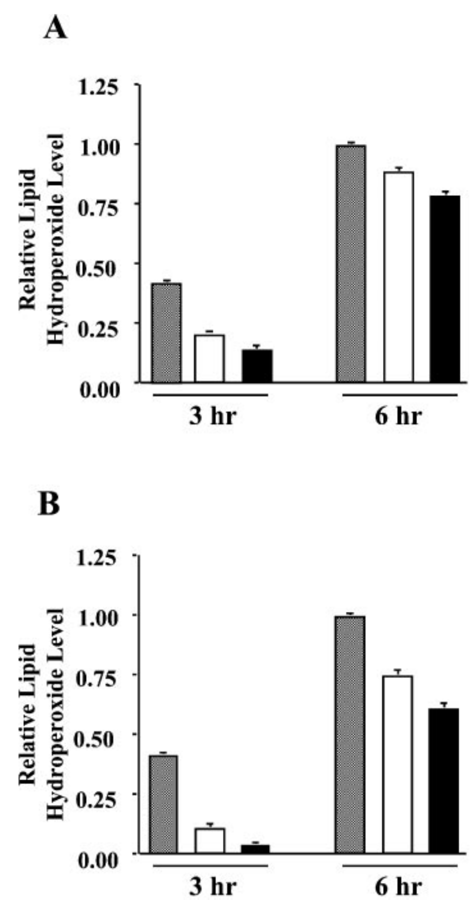

Figure 5. Increased ability of HDL from PON1 Tg mice on C57BL/6J background to protect against LDL oxidation. Human LDL was incubated at 37°C for 3 or 6 hours with addition of buffer (stippled bars), wild-type C57BL/6J HDL (open bars), or PON1 Tg HDL (solid bars) in the presence of copper to induce oxidation. HDL was added at 0.25 mg/mL (A) or 0.5 mg/mL (B). Each treatment was performed in quadruplicate. At end of incubation, lipid hydroperoxide content of samples was determined. Values shown are relative lipid hydroperoxide levels with LDL-alone group at 6 hours defined as 1. ANOVA was performed for statistical analysis. For panel A, probability values of ANOVA for treatment groups, time of incubation, and treatment groups×time of incubation were $P<0.0001$, $P<0.0001$, and $P=0.004$, respectively. For panel B, probability values of ANOVA for treatment groups, time of incubation, and treatment groups×time of incubation were $P<0.0001$, $P<0.0001$, and $P=0.08$, respectively. Experiments were repeated 3 times with similar results.

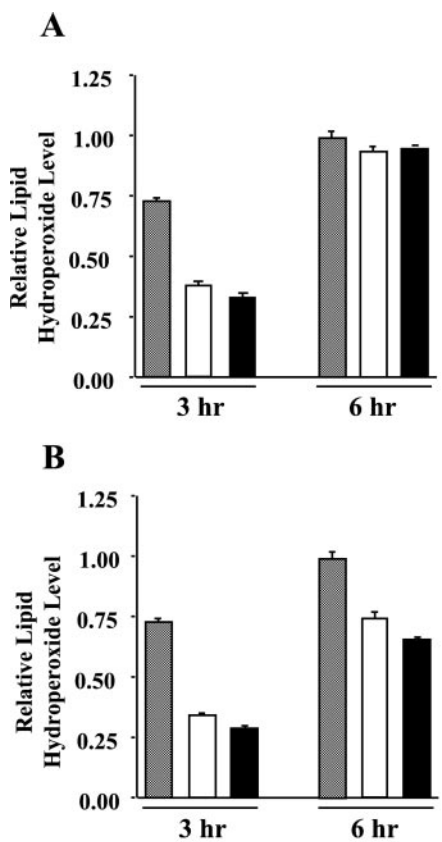

Figure 6. Increased ability of HDL from PON1 Tg mouse on an apoE KO background to protect against LDL oxidation. Human LDL was incubated at 37°C for 3 or 6 hours with addition of buffer (stippled bars), apoE KO HDL (open bars), or PON1 Tg/apoE KO HDL (solid bars) in the presence of copper to induce oxidation. HDL was added at 0.25 mg/mL (A) or 0.5 mg/mL (B). Experimental conditions and statistical analysis were same as in Figure 5. For panel A, probability values of ANOVA for treatment groups, time of incubation, and treatment groups×time of incubation were $P<0.0001$, $P<0.0001$, and $P<0.0001$, respectively. For panel B, probability values of ANOVA for treatment groups, time of incubation, and treatment groups×time of incubation were $P<0.0001$, $P<0.0001$, and $P=0.0008$, respectively. Data shown are representative of 2 independent experiments.

isoprostane and core aldehydes),[23] and peroxidase-like activities that destroy lipid hydroperoxides, and H_2O_2.[9,24] Thus, PON1 appears to exert its antiatherogenic effects mainly through its antioxidative functions. In addition to preventing LDL oxidation, PON1 may preserve other functions of HDL, such as reverse cholesterol transport, by reducing oxidative damage to HDL.[9] We also observed a 44% reduction of aortic MCP-1 expression in the PON1 Tg/apoE KO mice compared with their apoE KO littermates (Figure 4B). MCP-1, a chemokine induced by minimally oxidized LDL, plays a key role in monocyte recruitment and fatty streak formation. Deficiency in MCP-1 or its receptor, chemokine receptor-2, resulted in reduced atherosclerotic lesion formation in genetically altered mice.[25] Our results are consistent with an antiatherosclerotic role for PON1 upstream from MCP-1 induction, most likely by increasing the antioxidative activity of HDL and subsequently reducing the levels of oxidized LDL in the arterial wall.

Human epidemiological studies have revealed an association between low PON1 levels and an increased risk for coronary artery disease.[10–12] In the present study, we observed that a moderate increase in PON1 levels protects against atherosclerotic lesion formation in the PON1 Tg mice, compared with the wild-type mice, at both the early fatty streak stage (B6 model) (Figure 3) and the intermediate- to advanced-lesion stage (apoE KO model) (Figure 4A). Thus, PON1 may be a potential therapeutic agent for the prevention and/or treatment of atherosclerosis. Consistent with its ability to reduce cardiovascular mortality,[26] a recent study has demonstrated that moderate alcohol consumption increases plasma HDL, apoA-I, and PON1 levels in volunteers.[27] Also, cigarette smoking is associated with reduced serum PON1 activity.[28] Interestingly, flavonoids, such as glabridin (found in licorice) and quercetin (found in red wine), have been shown to scavenge reactive oxygen species and preserve the anti-oxidative functions of PON1 in vitro.[29] Supplementation of flavonoids protects LDL against oxidation and attenuates atherosclerosis in animal models.[30] Therefore, it will be interesting to examine whether a combined supplementation of flavonoids (or other antioxidants) and PON1 will exert a synergistic effect on protection against LDL oxidation and atherosclerosis in animal models. Further analysis of the regulation of PON1 levels in humans may yield promising avenues for atherosclerosis therapy.

Acknowledgments

This work was supported by the US Public Health Service (grant HL-30568 to Dr Lusis) and by the American Heart Association (Western States Affiliate Grant 0060040Y to Dr Shih). We thank Dr Clement Furlong for providing PON1 cDNA and antibody and Thomas J. Fielder for DNA microinjection. We thank Janet Danciger, Sharda Charugundla, Jack Wong, and John Miller for excellent technical assistance.

References

1. Lusis AJ. Atherosclerosis. *Nature.* 2000;407:233–241.
2. Glass CK, Witztum JL. Atherosclerosis. the road ahead. *Cell*. 2001;104:503–516.
3. Steinberg D. Low density lipoprotein oxidation and its pathobiological significance. *J Biol Chem.* 1997;272:20963–20966.
4. Aviram M, Rosenblat M, Etzioni A, et al. Activation of NADPH oxidase required for macrophage-mediated oxidation of low-density lipoprotein. *Metabolism*. 1996;45:1069–1079.
5. Tall AR. Plasma high density lipoproteins: metabolism and relationship to atherogenesis. *J Clin Invest*. 1990;86:379–384.
6. Hassett C, Richter RJ, Humbert R, et al. Characterization of cDNA clones encoding rabbit and human serum paraoxonase: the mature protein retains its signal sequence. *Biochemistry*. 1991;30:10141–10149.
7. Blatter MC, James RW, Messmer S, et al. Identification of a distinct human high-density lipoprotein subspecies defined by a lipoprotein-associated protein, K-45: identity of K-45 with paraoxonase. *Eur J Biochem*. 1993;211:871–879.
8. La Du BN. Human serum paraoxonase/arylesterase. In: Kalow W, ed. *Pharmacogenetics of Drug Metabolism*. New York, NY: Pergamon Press; 1992:51–91.
9. Aviram M, Rosenblat M, Bisgaier CL, et al. Paraoxonase inhibits high-density lipoprotein oxidation and preserves its functions: a possible peroxidative role for paraoxonase. *J Clin Invest*. 1998;101:1581–1590.
10. Mackness MI, Durrington PN, Ayub A, et al. Low serum paraoxonase: a risk factor for atherosclerotic disease? *Chem Biol Interact*. 1999;119–120:389–397.
11. Jarvik GP, Rozek LS, Brophy VH, et al. Paraoxonase (PON1) phenotype is a better predictor of vascular disease than is PON1(192) or PON1(55) genotype. *Arterioscler Thromb Vasc Biol*. 2000;20:2441–2447.

12. James RW, Leviev I, Ruiz J, et al. Promoter polymorphism T(-107)C of the paraoxonase PON1 gene is a risk factor for coronary heart disease in type 2 diabetic patients. *Diabetes*. 2000;49:1390–1393.
13. Shih DM, Gu L, Xia YR, et al. Mice lacking serum paraoxonase are susceptible to organophosphate toxicity and atherosclerosis. *Nature*. 1998;394:284–287.
14. Shih DM, Xia YR, Wang XP, et al. Combined serum paraoxonase knockout/apolipoprotein E knockout mice exhibit increased lipoprotein oxidation and atherosclerosis. *J Biol Chem*. 2000;275:17527–17535.
15. Jiang ZY, Hunt JV, Wolff SP. Ferrous ion oxidation in the presence of xylenol orange for detection of lipid hydroperoxide in low density lipoprotein. *Anal Biochem*. 1992;202:384–389.
16. Rimm EB, Stampfer MJ. Antioxidants for vascular disease. *Med Clin North Am*. 2000;84:239–249.
17. Kromhout D. Fatty acids, antioxidants, and coronary heart disease from an epidemiological perspective. *Lipids*. 1999;34:S27–S31.
18. Spencer AP, Carson DS, Crouch MA. Vitamin E and coronary artery disease. *Arch Intern Med*. 1999;159:1313–1320.
19. van de Vijver LP, Kardinaal AF, Grobbee DE, et al. Lipoprotein oxidation, antioxidants and cardiovascular risk: epidemiologic evidence. *Prostaglandins Leukot Essent Fatty Acids*. 1997;57:479–487.
20. Evans RW, Shaten BJ, Day BW, et al. Prospective association between lipid soluble antioxidants and coronary heart disease in men: the Multiple Risk Factor Intervention Trial. *Am J Epidemiol*. 1998;147:180–186.
21. Pryor WA. Vitamin E and heart disease: basic science to clinical intervention trials. *Free Radic Biol Med*. 2000;28:141–164.
22. Afridi N, Keaney JF. Animal studies on antioxidants. *J Cardiovasc Risk*. 1996;3:358–362.
23. Ahmed Z, Ravandi A, Maguire GF, et al. Multiple substrates for paraoxonase-1 during oxidation of phosphatidylcholine by peroxynitrite. *Biochem Biophys Res Commun*. 2002;290:391–396.
24. Aviram M, Hardak E, Vaya J, et al. Human serum paraoxonases (PON1) Q and R selectively decrease lipid peroxides in human coronary and carotid atherosclerotic lesions: PON1 esterase and peroxidase-like activities. *Circulation*. 2000;101:2510–2517.
25. Peters W, Charo IF. Involvement of chemokine receptor 2 and its ligand, monocyte chemoattractant protein-1, in the development of atherosclerosis: lessons from knockout mice. *Curr Opin Lipidol*. 2001;12:175–180.
26. Abramson JL, Williams SA, Kramholz HM, et al. Moderate alcohol consumption and risk of heart failure among older persons. *JAMA*. 2001;285:1971–1977.
27. van der Gaag MS, van Tol A, Scheek LM, et al. Daily moderate alcohol consumption increases serum paraoxonase activity: a diet-controlled, randomised intervention study in middle-aged men. *Atherosclerosis*. 1999;147:405–410.
28. James RW, Leviev I, Righetti A. Smoking is associated with reduced serum paraoxonase activity and concentration in patients with coronary artery disease. *Circulation*. 2000;101:2252–2257.
29. Aviram M, Rosenblat M, Billecke S, et al. Human serum paraoxonase (PON 1) is inactivated by oxidized low density lipoprotein and preserved by antioxidants. *Free Radic Biol Med*. 1999;26:892–904.
30. Fuhrman B, Aviram M. Flavonoids protect LDL from oxidation and attenuate atherosclerosis. *Curr Opin Lipidol*. 2001;12:41–48.

Circulation

Decreased Atherosclerotic Lesion Formation in Human Serum Paraoxonase Transgenic Mice

Aaron Tward, Yu-Rong Xia, Xu-Ping Wang, Yi-Shou Shi, Christina Park, Lawrence W. Castellani, Aldons J. Lusis and Diana M. Shih

Circulation. 2002;106:484-490; originally published online July 1, 2002;
doi: 10.1161/01.CIR.0000023623.87083.4F
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Print ISSN: 0009-7322. Online ISSN: 1524-4539