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Determination of LOX-1-ligand activity in mouse plasma with a chicken monoclonal antibody for ApoB

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Abstract

Oxidized LDL (OxLDL) is implicated in endothelial dysfunction as well as the formation and progression of atherosclerosis. It has become evident that the atherogenic properties induced by OxLDL are mainly mediated via lectin-like OxLDL receptor-1 (LOX-1). Over the past decade, much research has been performed to investigate lipid metabolism and atherogenesis using genetically engineered mice. To understand the significance of OxLDL, methods to measure the levels of OxLDL in these experimental animals should be established. Utilizing a chicken monoclonal antibody technique, here, we generated anti-human ApoB antibodies that are able to recognize mouse VLDL/LDL. These antibodies were selected from single chain fragment of variable region (scFv) phage library constructed from chickens immunized with human LDL. One of these antibodies, HUC20, was reconstructed into IgY form. Immunohistochemical analysis revealed that this novel antibody specifically stains atherosclerotic lesions of ApoE-deficient mice, associated with Oil red O positive and macrophage-antigen-positive regions.

Furthermore, in combination with recombinant LOX-1, a sandwich enzyme immunoassay was developed to measure the levels of LOX-1 ligands in mouse plasma. The sandwich enzyme immunoassay revealed a dramatic increase in the level of LOX-1 ligands in the plasma of ApoE-deficient mice fed high-fat diet, suggesting a link between the level of LOX-1-ligands and the progression of atherosclerosis in mice. Hence, the chicken anti-ApoB monoclonal antibody HUC20 developed here, could be a useful tool to analyze the role of ApoB-containing lipoprotein in atherogenesis in mice.

Keywords: LOX-1; Oxidized LDL; Mouse apolipoprotein B; Atherosclerosis

1. Introduction

Oxidatively modified low-density lipoprotein (LDL) has been implicated in endothelial dysfunction as well as the progression of atherosclerosis [1–3]. In response to stimulation of oxidized LDL (OxLDL), the production of nitric oxide is impaired and expression of chemoattractants for monocytes, leukocyte adhesion molecules, and growth factors for smooth muscle cells are induced in endothelial cells. These cellular events contribute to the formation of atherosclerotic lesions. Lectin-like OxLDL receptor-1 (LOX-1) was originally identified as a receptor for OxLDL expressed in vascular endothelial cells [4], and it has become evident that these atherogenic events induced by OxLDL are mainly mediated via LOX-1. Furthermore, we demonstrated significant *in vivo* roles of LOX-1 using genetically modified mice. Recently, we showed that deletion of LOX-1 in LDLR knockout (KO) mice led to a reduction in atherogenesis in association with a reduction in proinflammatory and pro-oxidant signals [5]. On the other hand, mice overexpressing LOX-1 in coronary vessels and cardiomyocytes showed accumulation of

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OxLDL in coronary arteries and inflammatory vasculopathy in a hyperlipidemic mouse model [6]. Thus, there is accumulating evidence that the interaction of OxLDL with LOX-1 plays an essential role in endothelial activation and/or dysfunction in atherosclerosis.

Over the last decade, progress in research on lipoprotein metabolism and atherosclerosis has been achieved by extensive investigations using genetically engineered mice. For example, a great deal of research breakthroughs has been made using ApoE or LDL receptor KO to clarify the pathogenesis of atherosclerosis-based cardiovascular diseases and lipid disorder, since atherogenesis in these experimental mice share many characteristics with human atherosclerotic lesions. To understand the underlying mechanisms, it is important to reveal a causal linkage between not only the plasma levels of lipoproteins, but also the accumulation of OxLDL and the pathogenesis of atherosclerosis; therefore, a specific assay for OxLDL in rabbits was developed and the direct relationship between OxLDL and atherogenesis was demonstrated [7,8]. However, there has been no tool to evaluate the interaction between LOX-1 and LOX-1 ligands such as OxLDL in mice until now. Indeed, mice monoclonal antibodies against mice ApoB-100 or ApoB-48 were previously generated, but these mice antibodies are not suitable for immunohistochemical study because of cross-reactivity of the secondary antibody for endogenous immunoglobulin.

In some cases, it is difficult to use mammals to create antibodies for biomolecules that have attained high levels of conservation in mammals. However, even in such cases, the target antibodies can be made with ease by having bird species develop immunity against the molecules. In the present study, we generated a chicken monoclonal antibody against mouse ApoB-containing lipoproteins. Furthermore, we developed a novel sandwich enzyme immunoassay for LOX-1 ligands in mouse plasma by applying this novel antibody and recombinant LOX-1. Using this method, we investigated the linkage between LOX-1 ligand activity and the atherogenesis in mice.

2. Methods

2.1. Chicken and immunization

Three 1-month-old H-B15 inbred chickens were immunized intraperitoneally (i.p.) with 100 μg of human LDL (Chemicon, Temecula, CA) together with an equal amount of alum solution. The animals received three additional intraperitoneal injections of the corresponding antigen at 3-week intervals.

2.2. Selection of scFv phage displayed antibody

Three days after the final injection, spleen cells were isolated from immunized chickens. The RNA extraction from spleen cells, amplification of immunoglobulin variable region (V_H and V_L) genes and construction of scFv phage library were performed by methods described previously [9]. The scFv phage clones were selected by panning method using Nunc-Immuno Module (Nunc, Roskilde, Denmark) coated with human LDL. For selection of the specific phage clones, Nunc-Immuno Module was coated with 100 μl of 5 μg/ml human LDL, human ApoB (Chemicon), mouse VLDL/LDL and mouse HDL, respectively, at 4 °C overnight. The plates were then blocked with phosphate buffered saline (PBS) containing 20% (w/v) ImmunoBlock (DS Pharma, Osaka, Japan) at 4 °C overnight. One hundred μl of phage solution was added to each well and the plates were incubated at 37 °C for 1 h. After washing, 100 μl of peroxidase-conjugated anti-chicken Ig-Fab fragment antibody (Bethyl laboratories, Montgomery, TX) diluted with PBS containing 5% (w/v) ImmunoBlock was added to each well and the plates were incubated at 37 °C for 1 h. After five washings, 100 μl of *o*-phenylenediamine sulfate (Sigma Chemical, St. Louis, MO) was added and their optical density was measured at 490 nm.

2.3. Preparation of recombinant IgY

For construction of recombinant IgY (rIgY), heavy chain and light chain expression vectors [10] were used, with the exception that cloning of heavy and light chain leader sequences were amplified from genome DNA from the HUC2-13 chicken hybridoma cells [11]. Approximately 6×10^7 FreeStyle 293-F cells (Invitrogen, Carlsbad, CA) were co-transfected by lipofection with a total of 80 μg of constructed VH and VL plasmid DNA for rIgY expression. After 72 h of transfection, the rIgY was purified from the supernatants by a ProBond Resin purification system (Invitrogen). Purified rIgY was dialyzed against PBS, and concentration of the rIgY was measured using a BCA Protein Assay kit (Pierce Biotechnology, Rockford, IL). The specificity of the purified rIgY was examined by enzyme-linked immunosorbent assay (ELISA) and Western blotting analyses. The dinitrophenyl (DNP)-specific rIgY, B4 [12], was used as a control rIgY.

2.4. Preparation of recombinant LOX-1

cDNA encoding the extracellular domain of human LOX-1 was subcloned into pcDNA4 with chicken IgG light chain leader peptide and 6× His tag in *N*-terminus. FreeStyle 293-F cells (Invitrogen) were transiently transfected with the expression vector. Four days after transfection, the recombinant LOX1 was purified from the culture supernatant with Ni-NTA superflow (Qiagen, Germantown, MD) according to the manufacturer's instruction.

2.5. Sandwich ELISA for LOX-1 ligand activity

Recombinant LOX-1 (0.4 μg/well) was immobilized on 96-well plates (Maxisorp, Nunc) by incubating overnight at 4 °C in 50 μl of PBS. After two washes with PBS, the plates were blocked with 0.3 ml of 20% (v/v) ImmunoBlock (DS

Pharma) for 8 h at 4 °C. After three washes with PBS, the plates were incubated with 0.1 ml of the standard OxLDL or plasma diluted 40 times with EDTA–HEPES buffer [10 mM HEPES (pH 7.0), 150 mM NaCl, 2 mM EDTA]. Then, the plates were washed three times with PBS, and incubated for 1 h at room temperature with 0.5 μg/ml HUC20 in PBS containing 1% (w/v) BSA. After three washes with PBS, the plates were incubated for 1 h at room temperature with the peroxidase-conjugated goat anti-chicken IgG (H+L) (KPL, Gaithersburg, MD) diluted 2000 times with PBS containing 1% (w/v) BSA. After five washes with PBS, the substrate solution containing 3,3′,5,5′-tetramethylbenzidine (TMB solution, Bio-Rad Laboratories, Hercules, CA) was added to the plates and incubated at room temperature for 30 min. The reaction was terminated with 50 μl of 2 M sulfuric acid. Peroxidase activity was determined by measurement of absorbance at 450 nm.

3. Results

3.1. Isolation of phage clones that recognize both human and mouse ApoB

To obtain the antibodies against ApoB with broader interspecies cross-reactivity, we immunized chicken with human LDL. After immunization five times, a phage display library was constructed from splenocytes of the chickens that express the immunoglobulin variable region. After the fifth round of panning selection of the phages, the specificity of the concentrated phage library was examined by ELISA using human LDL, human ApoB, mouse VLDL/LDL, and mouse HDL. The condensed library reacted with human LDL, human ApoB and mouse VLDL/LDL, but not with mouse HDL (data not shown). Thirteen independent scFv clones were isolated from the condensed library. Among them, seven clones were cross-reactive with mouse VLDL/LDL (Fig. 1A), indicating that these antibodies recognize ApoB as common molecule between human ApoB and mouse VLDL/LDL.

3.2. Construction of recombinant IgY

One of the seven scFv antibodies recognizing both human and mouse ApoB, #20, was reconstructed into IgY form containing a histidine tag in the C-terminal and named as HUC20. The HUC20 IgY from 293-F cells was purified from the supernatant by nickel affinity resin. The purified HUC20 was detected as a single band (250 kDa) in SDS-PAGE under non-reducing condition and the band was also detectable by Western blot analysis using anti-chicken IgG antibody (data not shown).

The reactivity of the HUC20 as assessed by ELISA showed that HUC20 was reactive with human LDL, human ApoB, and mouse VLDL/LDL, but not with mouse HDL (Fig. 1B). The results of the HUC20 reactivity reproduced that of the original #20 scFv phage-antibody. In contrast,

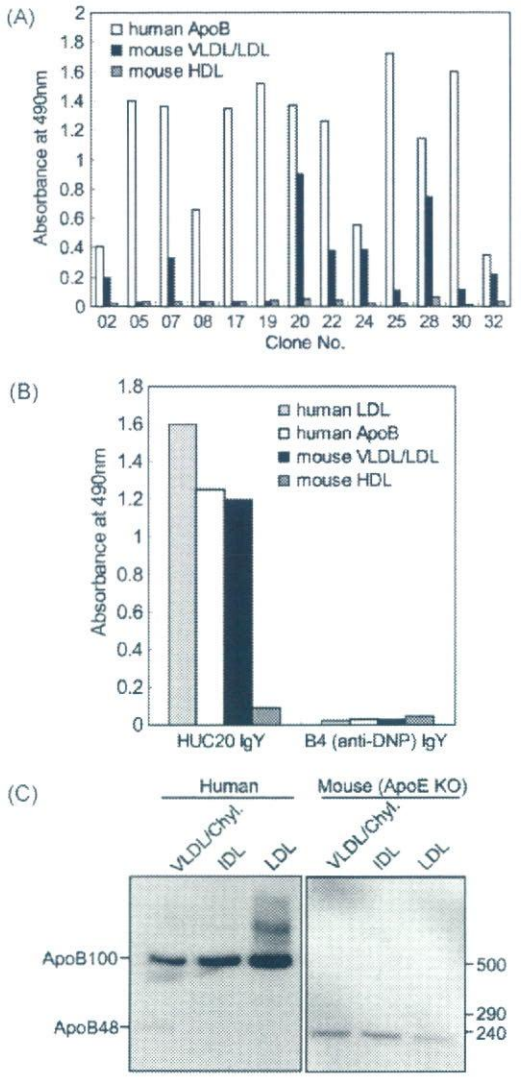

Fig. 1. Isolation of the antibody against human and mouse ApoB. (A) ELISA reactivity of scFv clones against human ApoB, mouse VLDL/LDL and mouse HDL, respectively. (B) ELISA reactivity of HUC20 rIgY against human LDL, human ApoB, mouse VLDL/LDL and mouse HDL. B4 rIgY was used as a negative control. (C) Western blotting analysis of lipoproteins with HUC20. Plasma from human and mouse (ApoE KO) was separated by sequential ultracentrifugation. Lipoproteins (100 ng) of each fraction were separated by SDS-PAGE followed by Western blotting with HUC20. HUC20 recognized ApoB-48 (approximately 240 kDa) as well as ApoB-100 (approximately 500 kDa).

a control rIgY, B4, reacted with none of the above antigens. To further investigate the recognition of HUC20, Western blotting analysis of lipoproteins from human and mouse (ApoE KO) plasma was performed. As shown in Fig. 1C, HUC20 recognized ApoB-100 (approximately 500 kDa) in VLDL/chylomicron, IDL, and LDL fractions from human as well as ApoB-48 (approximately 240 kDa) in VLDL/chylomicron from human. HUC20 also recognized ApoB-48 in VLDL/chylomicron, IDL, and LDL fractions from ApoE KO mice, in which plasma, ApoB-48-containing lipoproteins were highly accumulated [13]. Thus, HUC20

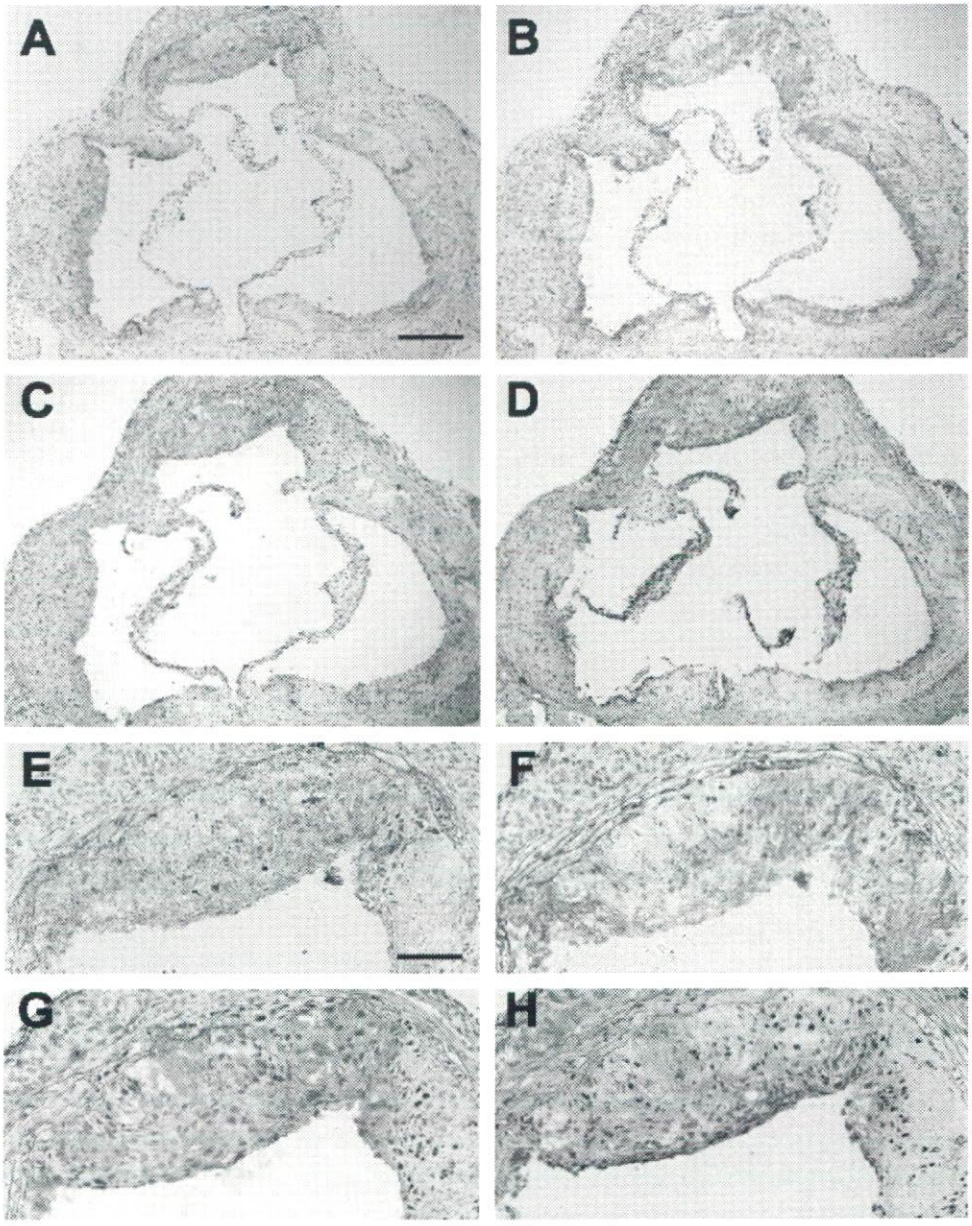

Fig. 2. Immunohistochemical detection of ApoB and LOX-1 ligand in atheroma. Sections of aortic root of 24-week-old ApoE KO mice stained with (A) Oil red O, (B) HUC20, (C) anti-macrophage antibody, (D) recombinant LOX-1 and (E)–(H) magnified view of A–D, respectively. Bars = 200 μm (A)–(D) and 100 μm (E)–(H).

recognizes both ApoB-100 and ApoB-48-containing lipoproteins.

3.3. Immunohistochemical detection of ApoB and LOX-1 ligand in atheroma

Utilizing HUC20, we performed immunohistochemical analyses of atheroma in aortic root of ApoE KO mice fed HF (high fat) diet. The ApoB-like immunoreactivity detected by HUC20 (Fig. 2B and F) was well co-localized with the lipid deposits detected by the Oil red O staining (Fig. 2A and E), where macrophage-derived foam cells were accumulated (Fig. 2C and G). These findings are in good agreement with the results from other species including human [14,15].

We further characterized mouse atheroma by the use of recombinant LOX-1 to detect LOX-1 ligand-like activity in these lesions, which is postulated to recognize oxidatively modified lipoproteins. As shown in Fig. 2D and H, the lesions associated with intimal thickening were positive for LOX-1 ligand activity. The existence of both ApoB-like immunoreactivity and LOX-1 ligand-like activity in atheromatous lesions suggests that these lesions might contain ApoB-containing oxidatively modified lipoproteins.

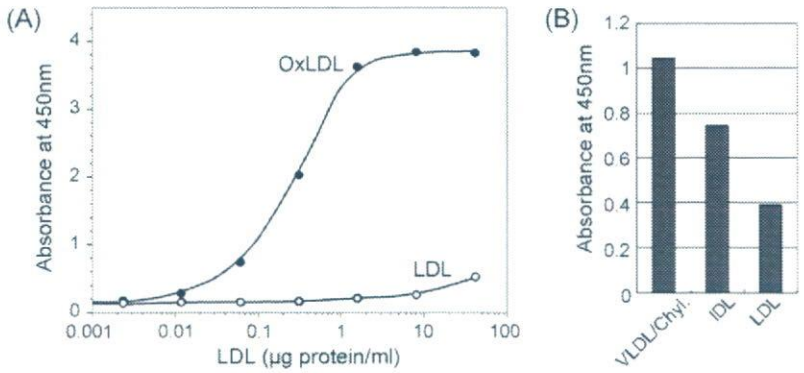

Fig. 3. Determination of LOX-1 ligand activity in human plasma. (A) Specificity of our ELISA system for modified LDL. The reactivity to OxLDL (filled circles) and LDL (open circles). (B) Reactivity of lipoproteins to LOX-1. Lipoproteins (10 μg protein/ml) isolated by sequential ultracentrifugation from human plasma were subjected to sandwich ELISA assay with LOX-1 and HUC20. Each fraction of lipoprotein reacted with LOX-1. The order of reactivity of LOX-1 was as follows: VLDL/chylomicron > IDL > LDL.

Table 1
Hemodynamic and plasma lipid indices

	WT control diet	WT HF diet	ApoE KO control diet	ApoE KO HF diet
Body weight (g)	23.9 ± 0.4	23.2 ± 0.2	22.6 ± 0.7	22.7 ± 1.1
SBP (mmHg)	113.7 ± 3.2	113.4 ± 3.8	109.9 ± 3.8	110.4 ± 4.8
MBP (mmHg)	82.2 ± 2.2	82.4 ± 4.1	77.8 ± 7.2	79.4 ± 3.4
DBP (mmHg	66.7 ± 2.1	66.8 ± 4.6	61.9 ± 2.2	64.2 ± 2.9
Heart rate (BPM)	535.0 ± 18.6	637.4 ± 21.1	536.9 ± 26.5	579.8 ± 15.7
Total cholesterol (mg/dl)	74.2 ± 4.2	191.4 ± 9.7	479.2 ± 40.2	3189.0 ± 162.5
Phospholipid (mg/dl)	165.3 ± 4.7	194.2 ± 11.0	315.4 ± 22.2	882.9 ± 42.4
Triglyceride (mg/dl)	53.9 ± 6.3	46.2 ± 6.7	136.7 ± 14.9	110.3 ± 4.8
HDL (mg/dl)	52.8 ± 2.1	39.4 ± 4.10	12.0 ± 2.5	14.1 ± 4.6

Data were collected at 9 weeks of age. Each animal ($n = 8$) fed control diet and after 2-week high-fat (HF) diet. SBP indicates systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure. Values are expressed as the mean ± S.E.M.

3.4. Detection of LOX-1 ligand activity in the plasma of human and ApoE KO mice

Combining the specificity of HUC20 for ApoB-containing lipoprotein and affinity of recombinant LOX-1 for OxLDL, we developed a sandwich ELISA system and applied it to quantify LOX-1 ligand activity in mouse plasma. This sandwich ELISA detected OxLDL as low as 1 ng/ml, but not native LDL even at the concentration of 10 μg/ml (Fig. 3A). Furthermore, we examined the characterization of the LOX-1 ligand lipoproteins in plasma. For the purpose, lipoprotein fractions (VLDL/chylomicron, IDL, and LDL) isolated by sequential ultracentrifugation from pooled plasma of human were subjected to sandwich ELISA assay with LOX-1 and HUC20. As shown in Fig. 3B, LOX-1 recognizes each fraction of lipoprotein. The order of reactivity of LOX-1 was as follows: VLDL/chylomicron > IDL > LDL.

Next, using this sandwich ELISA system, the alterations of the plasma levels of LOX-1 ligand activity in mice model of atherosclerosis were evaluated. We measured the plasma levels of LOX-1 ligand activity from wild type- or ApoE KO-mice fed normal or HF diet. LOX-1 ligand activity in the plasma of WT and ApoE KO mice fed normal diet was 5 ± 1 ng/ml and 30 ± 3 ng/ml, respectively. As shown in Table 1, HF diet significantly increased plasma cholesterol level in both wild type- and ApoE KO-mice. Concomitantly, LOX-1 ligand activities in the plasma of WT and ApoE KO mice were elevated as 71 ± 13 ng/ml and 1145 ± 115 ng/ml, respectively (Fig. 4A). The dilution curve of the plasma from ApoE KO mouse fed HF diet was accurately plotted on the line of standard curve of OxLDL, suggesting the plasma concentration of LOX-1 ligand is estimated well by reference to OxLDL (Fig. 4B).

4. Discussion

In this study we generated a novel chicken monoclonal antibody, HUC20, that recognizes mouse ApoB as well as that of human. The reactivity of HUC20 is specific and sensitive enough to detect mouse ApoB-containing lipoproteins in tissue by immunohistochemistry and those in plasma by enzyme immunoassay. Further, this sandwich enzyme immunoassay for LOX-1 ligands, which we developed by combining HUC20 and recombinant LOX-1, is sensitive enough to detect the increase of ApoB-containing LOX-1-ligands in mice fed a HF diet.

Well-known coronary risk factors such as hyperlipidemia, hypertension, diabetes, and metabolic syndrome induce oxidative stress. Under enhanced oxidative stress, the lipids

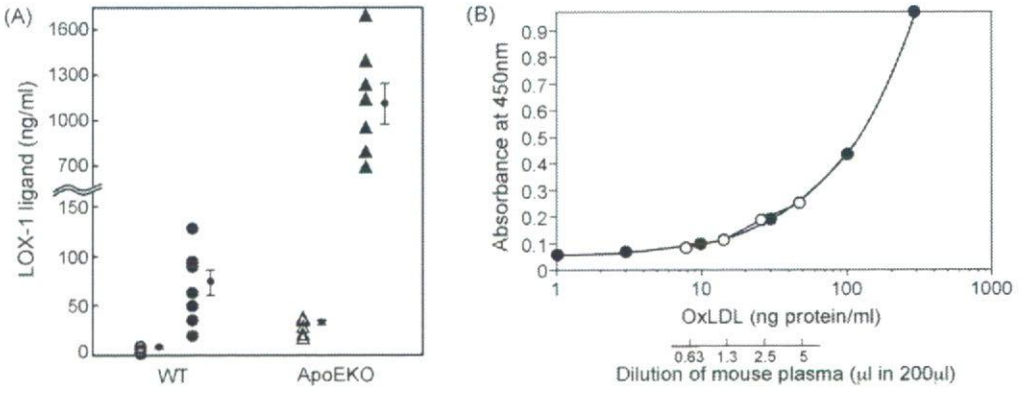

Fig. 4. Determination of LOX-1 ligand activity in plasma of ApoE KO mice. (A) Individual plasma LOX-1 ligand levels in WT mice fed control diet and HF diet (open and filled circles) and ApoE KO mice fed control and HF diet (open and filled triangles). Each bar represents the mean ± S.E.M., $n = 8$. (B) ELISA calibration curve for OxLDL in assay buffer (filled circles) and comparison with dilution curve for ApoE KO (2-week high-fat diet) plasma sample (open circles).

retained in the arterial wall are susceptible to oxidative modification. The oxidized lipids formed induce vascular inflammation, which, in turn, promotes the process of atherosclerosis. Among the oxidized lipids, OxLDL plays a crucial role in the pathogenesis of atherosclerosis. Various biomarkers have been proposed to evaluate the redox state and the plasma levels of OxLDL, such as isopentanes, 8-hydroxy-2′-deoxyguanine. Previous epidemiological studies demonstrated that level of OxLDL is a potent risk factor for the onset of coronary artery diseases, even if the levels of cholesterol are within the normal range. Indeed, Ehara et al. demonstrated that the levels of OxLDL in patients with acute coronary syndrome were much higher than stable angina [16]. However, more direct linkage between the LDL oxidation and the progression of atherosclerosis has been vague in genetically engineered mice such as ApoE or LDL receptor KO mice, because of the lack of a specific assay for OxLDL in mouse plasma.

Chickens are useful for the acquisition of specific antibodies against proteins conserved among mammalian species. In the case of ApoB, the homology of ApoB-48 between human and mice is 78%, whereas that between human and chicken is 48%. Thus, it is difficult to raise specific antibodies against such conserved proteins like apoproteins. Using the chicken we can overcome such problems. Further, by the application of recombinant DNA technology using scFv phages, we can choose a single clone that is specific, sensitive, and suitable for particular use as an antibody. The chicken monoclonal antibody system has a merit in that scalable production is possible, as is common in monoclonal antibodies raised from other species. Another advantage of a chicken monoclonal antibody raised against the mouse is the ease of application to study in the mouse. Mouse antibodies are often unsuitable for investigation of mice themselves, because the secondary antibody against mouse immunoglobulin recognizes endogenous mouse immunoglobulin.

When considering the possibilities of raising genetically engineered mice as models for human diseases, including hyperlipidemia and atherosclerosis, it is crucial to develop and use analytical methods applicable to both human and mouse in order to understand disease and develop therapeutic strategies. Despite a common recognition for the importance of ApoB-containing lipoproteins and their oxidized form in the pathogenesis of atherosclerosis, immunological tools to dissect the problem in mice have not been well established. Here we successfully developed a chicken monoclonal antibody for ApoB and an ELISA system to determine ApoB-containing LOX-1 ligand, which can be applied for both human and mouse studies. These will give us the opportunity to analyze the precise roles of ApoB-containing lipoproteins and their oxidized form in various disease.

LOX-1 mediates endothelial dysfunction induced by chylomicron/remnants as well as modified LDL [17,18]. Therefore, the combination of recombinant LOX-1 and HUC20 which recognizes both ApoB-48 and ApoB-100, could detect atherogenic ApoB-containing lipoproteins in both VLDL/LDL and chylomicron/remnants fractions by the present ELISA system. HUC20 might also be needed for a certain tool for the detection of ApoB-48 in atherosclerosis lesions.

Indeed in the present study, we showed the accumulation of ApoB-containing lipoproteins and LOX-1 ligand in atheroma. We also found that LOX-1 ligand activity was significantly elevated in the plasma of ApoE KO mice fed HF diet. Furthermore, removal of LOX-1 ligands from plasma by the ectopic expression of LOX-1 in mouse liver significantly suppressed the progression of atherosclerosis (Katagiri H, unpublished data). As well known, ApoE KO mice show significant increase in HF diet of VLDL and chylomicron/remnants rather than LDL. Therefore, it should be noted that LOX-1 ligand activity we measured in this mice model might reflect the activity in the fractions of VLDL and chylomicron/remnants. In any case, the data suggest that the accumulation of ApoB-containing LOX-1 ligands might enhance the progression of atherosclerosis in mice, and LOX-1 ligand level would also be an important indicator for the

diagnosis and the evaluation of atherosclerosis and ischemic heart diseases in the genetically modified mouse model and in humans.

In summary, we generated a chicken monoclonal antibody HUC20 that recognizes both mouse and human ApoB, which can detect LDL in mouse atheroma. Furthermore, we developed an ELISA assay for OxLDL/VLDL that measures ApoB-containing LOX-1 ligands. This antibody will be a useful tool for research with regard to dyslipidemia, atherosclerosis, and ischemic heart diseases.

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Essential Role of NOXA1 in Generation of Reactive Oxygen Species Induced by Oxidized Low-Density Lipoprotein in Human Vascular Endothelial Cells

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Oxidative stress induced by superoxide plays an important role in pathogenesis of cardiovascular diseases. NAD(P)H oxidase is a principal enzymatic origin for superoxide in vasculature. Recently, novel homologues of cytosolic components of NAD(P)H oxidase, Nox organizer 1 (NOXO1) and Nox activator 1 (NOXA1), are identified. On the other hand, oxidized low-density lipoprotein (ox-LDL) generates reactive oxygen species (ROS) in endothelial cells via lectin-like oxidized low-density lipoprotein receptor-1 (LOX-1). In the present investigation, the authors examined the expression, the regulation, and the role of NOXA1 in the generation of ROS in endothelial cells. The expression of NOXA1 was confirmed by reverse transcriptase–polymerase chain reaction (RT-PCR). Dihydroethidium method showed that ox-LDL and angiotensin II increased the generation of intracellular ROS. Once the expression of $p22^{phox}$ or NOXA1 was suppressed by siRNA, the generation of ROS induced by ox-LDL and angiotensin II were potently decreased. Moreover, the expression of NOXA1 was increased by ox-LDL in a time- and dose-dependent manner. In conclusion, endothelial NOXA1 plays an essential role in generation of ROS. Ox-LDL not only increased the generation of ROS via LOX-1, but also enhanced the expression of NOXA1 in endothelial cells. NOXA1 is likely a key player that links ox-LDL with the activation of endothelial NAD(P)H oxidase.

Keywords Endothelium, NAD(P)H Oxidase, Oxidized LDL, $p22^{phox}$, ROS

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Oxidative stress induced by superoxide in vasculature plays an in important role in pathogenesis of various cardiovascular diseases, including atherosclerosis, hypertension, ischemia-reperfusion injury, and vascular remodeling. To date, various enzymatic origins for reactive oxygen species (ROS) in the vasculature have been proposed, including xanthine oxidase, myeloperoxidase, lipoxygenase, and NAD(P)H oxidase. Among these, NAD(P)H oxidase is the most important origin of ROS in human coronary arteries (Kobayashi et al. 2003; Azumi et al. 2002). NAD(P)H oxidase was originally identified as a principal enzymatic origin in phagocytes, and this phagocyte NAD(P)H oxidase is located on a very front line in host-defense system. The phagocyte NAD(P)H oxidase is dormant in resting cells, but becomes activated to produce superoxide, a precursor of microbicidal oxidants, by interacting with the adaptor proteins $p47^{phox}$ and $p67^{phox}$ as well as the small GTPase Rac. Griendling et al. reported that vascular cells such as vascular smooth muscle cells and endothelial cells possess the activity to generate ROS in a NADH- and NADPH-dependent manner (Griendling et al. 1994). Progress in this field has revealed the molecular identification of nonphagocytic NAD(P)H oxidase in the past few years. Besides the components of phagocyte NAD(P)H oxidase, several protein homologs to $gp91^{phox}$/Nox2 were identified (the Nox family oxidases) (Lambeth 2004; Geiszt and Leto 2004). Recently, homologs of $p47^{phox}$ and $p67^{phox}$ were reported and shown to be required for activation of Nox1. The $p47^{phox}$ homolog is named as NOXO1 (NOX organizer 1), whereas the $p67^{phox}$ homolog is named as NOXA1 (NOX activator 1) (Banfi et al. 2003; Geiszt et al. 2003; Takeya et al. 2003; Takeya and

Sumimoto 2003). However, their functional roles in the activation of vascular NAD(P)H oxidase remains to be elucidated.

Clinical investigations have demonstrated that well-known coronary risk factors such as diabetes, hyperlipidemia, hypertension, smoking, and metabolic syndrome are associated with oxidative stress. Under the oxidative stress, low-density lipoprotein (LDL) particle, which are trapped in the vessel wall, are oxidative modified. Formed oxidized low-density lipoprotein (ox-LDL) is a potent inducer of endothelial injury with associated its dysfunction. ox-LDL induces the inflammatory responses, including the up-regulation of adhesion molecules, cytokines, and chemotactic factors. These cellular events are mediated via lectin-like oxidized low-density lipoprotein receptor-1 (LOX-1)–mediated pathway. LOX-1, a multiligand receptor, was originally identified as the major ox-LDL receptor in endothelial cells (Sawamura et al. 1997). The expression of LOX-1 in endothelial cells is markedly increased in vitro by cytokines and also is induced in vivo in hypertension, diabetes, and hyperlipidemia in animal models (Li et al. 2004; Nagase et al. 2000; Chen et al. 2000). Ligand binding to LOX-1 induces superoxide generation, which is accompanied by reduction of nitric oxide in endothelial cells (Cominacini et al. 2001). The activation of LOX-1 by ox-LDL induced the generation of ROS via NAD(P)H oxidase. We previously demonstrated that the NAD(P)H oxidase is expressed in coronary arteries of patients with ischemica heart disease (Kobayashi et al. 2003; Azumi et al. 2002). Further, LOX-1 is up-regulated in atherosclerotic lesions (Chen et al. 2000; Kataoka et al. 1999). Therefore, the clarification of the interaction of NAD(P)H oxidase and LOX-1 provides a new insight into understanding the pathogenesis of atherosclerosis-based ischemic heart diseases. In this study, we investigated the functional roles of NOXA1 in regulation of endothelial NAD(P)H oxidase and its interaction of LOX-1.

MATERIALS AND METHODS

Cell Culture

EAhy926, a continuous human umbilical vein endothelial cells line, was cultured in Dulbecco's modified Eagle's medium (Sigma Chemical, St. Louis, MO, USA) with 10% fetal bovine serum (JRH Biosciences, Lenexa, KS, USA), and with 100 IU/mL antibiotic-antimyotic.

Preparation of Oxidized Lipoprotein

LDL was isolated by sequential ultracentrifugation from healthy human plasma, as described previously (Sawamura et al. 1997). LDL was oxidatively modified by exposing to 7.5 mol/L $CuSO_4$ for 16 h at 37°C at the protein concentration of 3 mg/mL in phosphate-buffered saline. The degree of oxidation was estimated by measuring the amount of thiobarbituric acid-reactive substances (TBARS) and the relative electrophoretic mobility (REM) in agarose gel compared with native LDL.

Small Interfering RNA

NOXA1 and $p22^{phox}$ expression were inhibited by the Stealth small interfering RNA (RNAi) (Invitrogen, CA, USA). The siRNA target sequences were as follows: 5′-GGGCATTTGACC AAGCCGTGACCAA-3′ and 5′-GCCATTGCGAGCGGCATC TACCTAC-3′, respectively. EAhy926 were transfected with Stealth RNAi at a final concentration of 250 nmol/L by the use of oligofectamine reagent (Invitrogen). The Stealth RNAi Negative Control Duplexes with similar G/C content (Invitrogen) were used as a negative control.

RT-PCR

Total RNA was isolated from cultured EAhy926 using TRIzol (Invitrogen) according to the manufacturer's instructions. Complementary DNA was prepared using a reverse transcriptase–polymerase chain reaction (RT-PCR) kit (RETROscript; Ambion, TX, USA). PCR reactions were performed with *Taq* polymerase using the following specific primers. The primer sequences were as follows: NOXA1 sense primer: 5′-TGGGAGG TGCTACACAATGTG-3′, antisense primer: 5′-GACCTCTGT CTCTGCATCGA-3′; $p22^{phox}$ sense primer: 5′-GTTTGTGTG CCTGCTGGAGT-3′, antisense primer: 5′-TGGGCGGCTGCT TGATGGT-3′. NOXA1 cDNA amplification was performed in 35 cycles: sample were heated to 94°C for 1 min, cooled to 60°C for 1 min, and then heated at 72°C for 1 min. p22phox cDNA amplification was performed in 25 cycles: samples were heated to 94°C for 1 min, cooled to 59°C for 1 min, and then heated at 72°C for 1 min. PCR products were separated using 1% agarose gels stained with ethidium bromide and visualized under ultraviolet (UV) light. PCR products were purified and further analyzed by DNA sequencing using an ABI Prism BigDye Terminator Cycle Sequencing kit on an ABI Prism 310 Genetic Analyzer. To measure the production of each mRNA, RT-PCR for human glutaldehyde-3-phosphate dehydrogenase (GAPDH) was also performed (sense primer 5′-ACGGATTTGGTCGTATTGGGC-3′, antisense primer 5′-TTGACGGTGCCATGGAATTTG-3′).

Evaluation of Intracellular Reactive Oxygen Species by Dihydroethidium Methods

Intracellular ROS was detected with dihydroethidium (Molecular Probes, Eugene, OR, USA). A confluent monolayer cells were stimulated with angiotensin II (10^{-7} mol/L) (Sigma Chemical) or ox-LDL for 1 h. After stimulation, they were treated with dihydroethidium (2 μmol/L) for 20 min at 37°C in the dark. The fluorescence intensity was measured using a laser-scanning confocal imaging system, and quantified using ImageJ software (National Institutes of Health).

Statistical Analysis

Data are presented as mean ± *SE*. Statistical analysis was performed by analysis of variance followed by Fisher's probable least significant difference (PLSD) test. A p value of less than .05 was considered to be statistically significant.

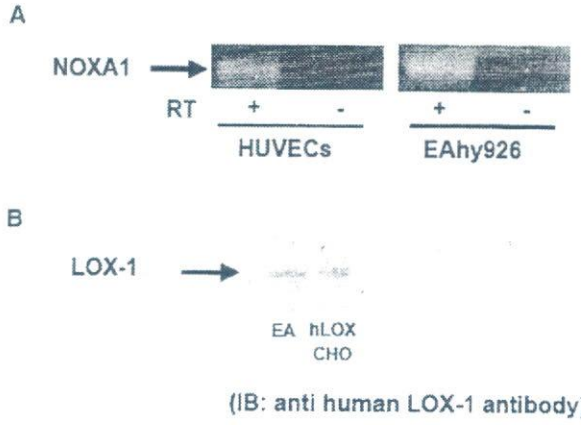

FIG. 1. Expression of NOXA1 and LOX-1 in human endothelial cells. RT-PCR confirmed the expression of NOXA1 in cultured HUVECs and its continuous cell line EAhy926 (*A*). Western blotting analysis confirmed the expression of LOX-1 in EAhy926. HLOX-CHO, which continuous expressed human LOX-1, was used as a positive control (*B*).

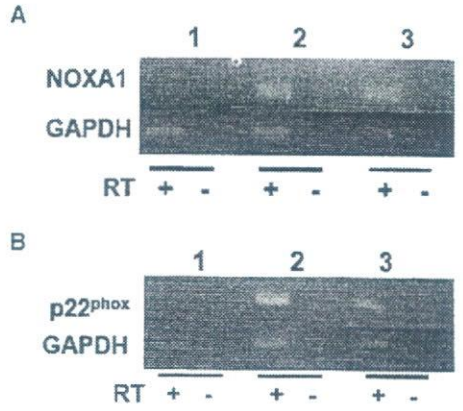

FIG. 2. Suppression of NOXA1 and $p22^{phox}$ by transfection of siRNA in endothelial cells. The expression of NOXA1 and $p22^{phox}$ were potently suppressed by their target siRNA. 1 = target Stealth RNAi; 2 = mock control, 3 = Stealth negative-control duplexes. Their mock control and scramble control had no effects (*A* and *B*).

RESULTS

NOXA1 and LOX-1 Were Expressed in Endothelial Cell Line

The expression of NOXA1, in human umbilical vein endothelial cells (HUVECs), was confirmed by RT-PCR. No RT-PCR product was present in the negative control in which RT was not performed. EAhy926, a continuous cell line of HUVECs, also expressed NOXA1 (Figure 1*A*). Sequencing of complementary DNA of NOXA1 obtained from HUVECs and EAhy926 were the same as reported before (data not shown) (Takeya et al. 2003). Thus, NOXA1 was expressed in endothelial cells. The expression of LOX-1 in EAhy926 was confirmed by Western blotting analysis. EAhy926 had the same sized band as hLOX-CHO cells, which permanently express human LOX-1 (Figure 1*B*).

NOXA1 and $p22^{phox}$ Were Essential for ROS Generation in Endothelial Cells

RT-PCR revealed that transfection with siRNA of NOXA1 and $p22^{phox}$ potently suppressed their expression in endothelial cells, whereas their mock control and scramble control had no effects (Figure 2).

Suppression of $p22^{phox}$ by siRNA significantly decreased the generation of intracellular ROS induced by ox-LDL (30 μg/mL) and angiotensin II (10^{-7}M) in endothelial cells evaluated by dihydroethidium method. Its mock control and scramble control had no effects (Figure 3). Similarly, the suppression of NOXA1 by siRNA induced a significant reduction of the generation of ROS (Figure 3).

The Expression of NOXA1 Was Increased by Ox-LDL in Endothelial Cells

The effect of ox-LDL on expression of NOXA1 was examined by RT-PCR. Incubation with ox-LDL for 12 h significantly increased the expression of NOXA1 in a dose-dependent manner (Figure 4*A*). Incubation with ox-LDL (30 μg/mL) moderately increased the expression of NOXA1 in a time-dependent manner, especially in 24 h (Figure 4*B*). Thus, ox-LDL not only increased the generation of intracellular ROS via LOX-1, but also enhanced the expression of NOXA1.

DISCUSSION

Vascular NAD(P)H oxidase, which regulates superoxide, plays an important role in pathogenesis of various cardiovascular disease (Kobayashi et al. 2003; Azumi et al. 2002; Brandes and Kreuzer 2005; Sorescu et al. 2002; Tojo et al. 2005). There is no direct evidence that NOXA1 is involved with endothelial NAD(P)H oxidase. The present investigation is the first study to demonstrate that NOXA1 is expressed in endothelial cells. Down-regulation of $p22^{phox}$ and NOXA1 by siRNA significantly suppressed the generation of intracellular ROS. Furthermore, the expression of NOXA1 was increased by ox-LDL in a time- and dose-dependent manner.

The active superoxide-generating subunit of NAD(P)H oxidase is the NOX protein. NOX1 activation requires membrane recruitment of NOXA1, which is normally mediated via binding to NOXO1. NOXO1 tethers to the $p22^{phox}$ even in the resting state. In the presence of NOXA1 and NOXO1, NOX1 produces superoxide without cell stimulants. The NOXA1-NOXO1 and NOXO1-$p22^{phox}$ interactions are both essential for NOX1 activity (Takeya et al. 2003; Miyano et al. 2006). On the other hand, NOXA1 as well as $p67^{phox}$ contains a small GTPase Rac-binding domain in the N-terminal region. The Rac-NOXA1 interaction at the membrane plays a crucial role in NOX1 activation. Rac directly participates in formation of the active NOX1 complex via binding to NOXA1 (Miyano et al. 2006; Ueyama et al. 2006). We previously demonstrated that the NAD(P)H oxidase is expressed in coronary arteries of patients with coronary artery disease, and $p22^{phox}$-based NAD(P)H oxidase plays a major

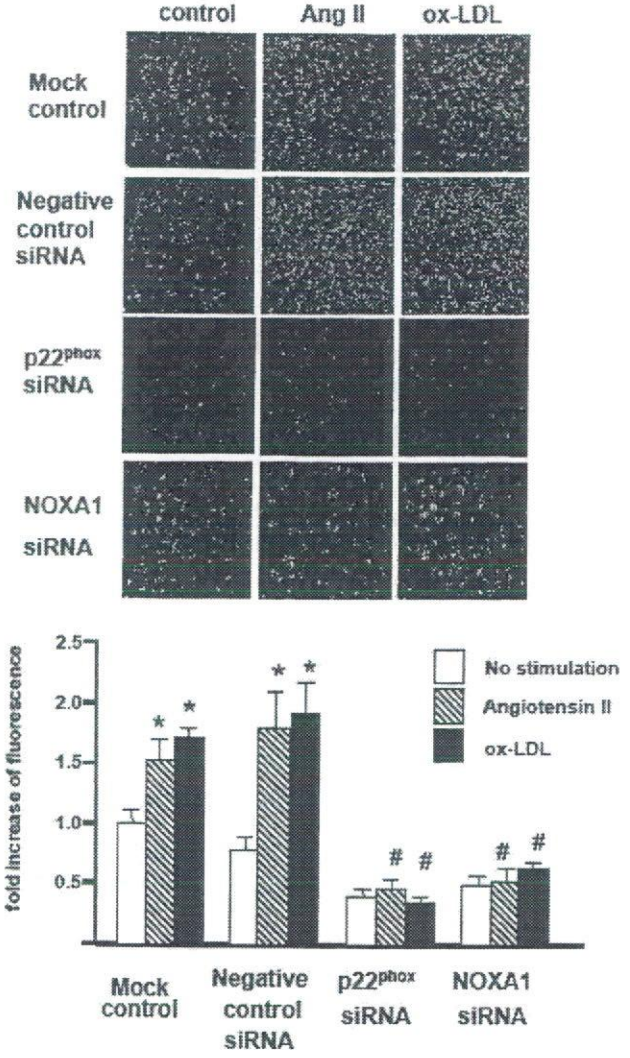

FIG. 3. The role of $p22^{phox}$ and NOXA1 to generate intracellular ROS in endothelial cells. Incubation with angiotensin II (10^{-7}M) or ox-LDL (30 μg/mL) induced the generation of intracellular ROS in endothelial cells, assessed by the dihydroethiduim methods. Suppression of $p22^{phox}$ by siRNA decreased the generation of intracellular ROS induced by angiotensin II or ox-LDL. Similarly, suppression of NOXA1 by siRNA induced a siginificant reduction of generation of ROS. Lower panels show quantitative analysis of the fluorescence intensity of dihydroethidium. $*p < .05$ versus no stimulation; $\#p < .05$ versus negative-control siRNA.

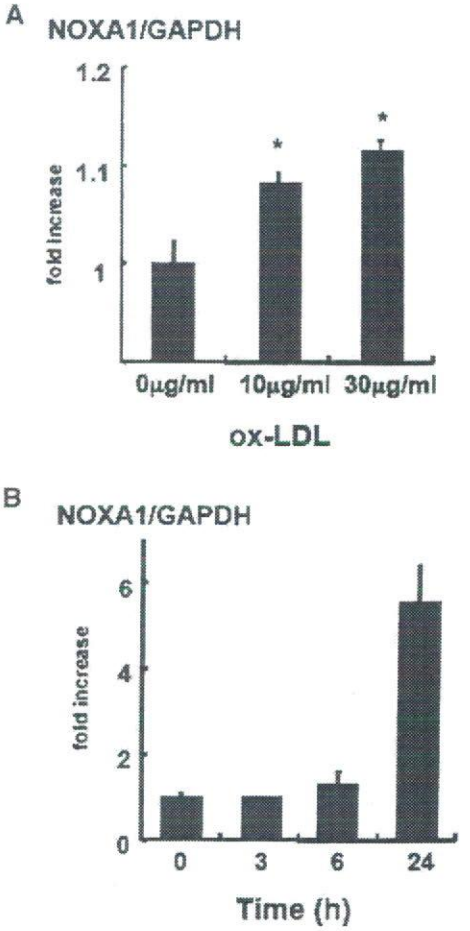

FIG. 4. The effects of ox-LDL on NOXA1 expression in endothelial cells. Endothelial cells were incubated with the indicated concentration of ox-LDL for 12 h (*A*) or incubated with ox-LDL (30 μg/mL) for the indicated time periods (*B*). After stimulation, expression of NOXA1 was assessed by RT-PCR. Data were plotted as mean ± *SE*. $*p < .01$ versus 0 μg/mL.

role in pathogenesis of atherosclerotic coronary artery disease (Kobayashi et al. 2003; Azumi et al. 2002). In the present investigation, NOXA1 was expressed in the endothelial cells and was essential on ROS generation. These findings suggest that not only endothelial $p22^{phox}$ but also endothelial NOXA1 is one of the quite important components of endothelial NAD(P)H oxidase, and that NOXA1 is a key player of in the pathogenesis of atherosclerotic coronary artery disease.

Interestingly, ox-LDL not only increased the generation of ROS via binding to LOX-1, but also enhances the expression of NOXA1 in a time- and dose-dependent manner in endothelial cells. Because NOXA1 is essential for the generation of ROS, it is interesting to speculate that there is a vicious cycle consisting of ox-LDL, NOXA-1, and LOX-1. That is to say, ox-LDL binds to LOX-1 and enhances the expression of NOXA1, then NOXA1 augments the generation of ROS. Furthermore, ROS induce the oxidative modification of LDL. In endothelial cells, the mechanism of generating ROS by LOX-1 is involved with endothelial NAD(P)H oxidase, especially NOX1, Rac, and NOXA1. NOXA1 is likely a key player, which links ox-LDL with the activation of endothelial NAD(P)H oxidase.

As described above, atherosclerotic cardiovascular disease is associated with oxidative stress. Clinical investigations show that coronary risk factors induced oxidative stress. Indeed, we demonstrated that the generation of ROS in coronary arteries of ischemic heart disease was markedly enhanced (Kobayashi et al. 2003; Azumi et al. 2002). Thus, oxidative stress may be a common pathway from coronary risk factors and atherosclerotic vascular diseases. Therefore, it can be thought that therapeutic interventions using antioxidant drugs can reduce the occurrence

of cardiovascular diseases (CVDs) and improve the survival and mortality of cardiovascular diseases. However, using antioxidants has not produced good results to prevent CADs in clinical trials, although there are few exceptions. Meta-analysis demonstrates that cardiovascular as well as cerebrovascular events did not differ between patients treated and those not treated with antioxidative vitamins (Hoogwerf and Young 2000; Lonn et al. 2001; Group HPSC 2002; Lee et al. 2005). Thus, at the present time, antioxidant drugs likely have no beneficial effect on cardiovascular disease. Precise reasons of the ineffectiveness of antioxidants for cardiovascular diseases remain to be elucidated. Besides harmful effects, ROS plays various physiological roles including host-defense system or intracellular signaling. Therefore, more specific agents may be necessary for the prevention and treatment for cardiovascular diseases. In the present investigation, the down-regulation of NOXA1 dramatically reduced the generation of ROS in endothelial cells. NOXA1 could be a novel therapeutic target of atherosclerosis-based heart disease from a view point of oxidative stress.

In conclusion, NOXA1 was expressed in vascular endothelial cells. Ox-LDL not only increased the generation of ROS via LOX-1, but also enhanced the expression of NOXA1. NOXA1 is likely a key player that links ox-LDL with the activation of endothelial NAD(P)H oxidase.

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Novel Gene Silencer Pyrrole-Imidazole Polyamide Targeting Lectin-Like Oxidized Low-Density Lipoprotein Receptor-1 Attenuates Restenosis of the Artery After Injury

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Abstract—Lectin-like oxidized low-density lipoprotein receptor-1 (LOX-1) is a membrane protein that can support the binding, internalization, and proteolytic degradation of oxidized low-density lipoprotein. The LOX-1 expression increases in the neointima after balloon injury. To develop an efficient compound to inhibit LOX-1, we designed and synthesized a novel gene silencer pyrrole-imidazole (PI) polyamide targeting the rat LOX-1 gene promoter (PI polyamide to LOX-1) to the activator protein-1 binding site. We examined the effects of PI polyamide to LOX-1 on the LOX-1 promoter activity, the expression of LOX-1 mRNA and protein, and neointimal hyperplasia of the rat carotid artery after balloon injury. PI polyamide to LOX-1 significantly inhibited the rat LOX-1 promoter activity and decreased the expression of LOX-1 mRNA and protein. After balloon injury of the arteries, PI polyamide to LOX-1 was incubated for 10 minutes. Fluorescein isothiocyanate–labeled PI polyamide was distributed to almost all of the nuclei in the injured artery. PI polyamide to LOX-1 (100 μg) significantly inhibited the neointimal thickening by 58%. PI polyamide preserved the re-endothelialization in the injured artery. PI polyamide significantly inhibited the expression of LOX-1, monocyte chemoattractant protein-1, intercellular adhesion molecule-1, and matrix metalloproteinase-9 mRNAs in the injured artery. The synthetic PI polyamide to LOX-1 decreased the expression of LOX-1 and inhibited neointimal hyperplasia after arterial injury. This novel gene silencer PI polyamide to LOX-1 is, therefore, considered to be a feasible agent for the treatment of in-stent restenosis. (***Hypertension*. 2008;52:86-92.)**

Key Words: basic science ■ endothelium ■ gene therapy ■ cytokines ■ polyamide ■ LOX-1 ■ restenosis

Coronary artery restenosis after angioplasty occurs in ≈30% of all patients.[1,2] Despite the widespread use of intracoronary stents, in-stent restenosis remains a major clinical problem, occurring in ≤50% of high-risk patients.[3] The development of neointimal hyperplasia after arterial injury contributes to the pathogenesis of restenosis. Several factors are involved in the initiation and progression of neointimal hyperplasia. Coronary arterial diseases are known to be associated with several risks, such as dyslipidemia, hypertension, smoking, and diabetes. A pivotal common factor in these risks is oxidative stress, which also induces restenosis of the coronary artery.[4]

The oxidized low-density lipoprotein (ox-LDL) is recognized to be a major cause of endothelial dysfunction in atherogenesis.[5] Lectin-like ox-LDL receptor-1 (LOX-1), a receptor for ox-LDL, is a membrane protein that is expressed in both the vascular endothelium and vascular-rich organs. LOX-1 can support the binding, internalization, and proteolytic degradation of ox-LDL.[6] The LOX-1 expression has been reported to significantly increase in the neointima after balloon injury in various animal models of neointimal hyperplasia, such as rats and rabbits. Hinagata et al[7] reported neointimal hyperplasia after balloon injury to be markedly attenuated by treatment with anti–LOX-1 antibody in a rat model. These findings suggest that LOX-1 expressed in the neointima is involved in the pathogenesis of restenosis after arterial injury, and, therefore, LOX-1 may be a potential therapeutic target for the prevention/treatment of neointimal hyperplasia and restenosis after arterial injury.

Pyrrole-imidazole (PI) polyamide is a powerful gene-regulating compound that can inhibit protein, including enhancers or repressors, DNA binding, and interaction by binding to the minor groove of double-helical DNA with high affinity and specificity.[8] PI polyamide was first identified from duocarmycin A and distamycin A, which recognize and bind DNA with sequence specificities and are small synthetic molecules com-

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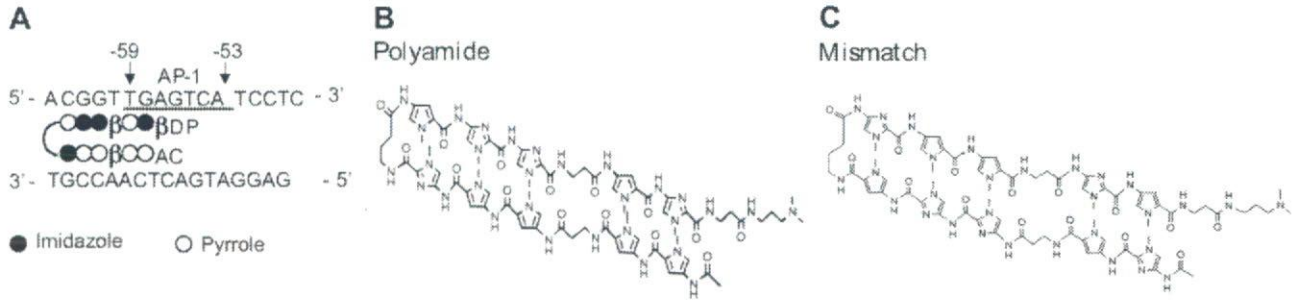

Figure 1. A, The target site of synthesized PI polyamide targeting rat LOX-1 promoter (PI polyamide to LOX-1). PI polyamide to LOX-1 was designed to span the boundary of the AP-1 binding site (−63 to −58) of the LOX-1 promoter. B and C, The structure of synthesized PI polyamide targeting rat LOX-1 promoter and mismatch polyamide. The mismatch polyamide was composed of scramble polyamides. Molecular weight=1669.

posed of the aromatic rings of *N*-methylpyrrole and *N*-methylimidazole amino acids.[9,10] PI polyamides are resistant to nucleases and do not require any particular delivery systems.[11] Various types of sequence-specific DNA-binding PI polyamides have been developed to control gene expression.[12] DNA recognition depends on a code of side-by-side pairing of pyrrole and imidazole in the minor groove. A pairing of imidazole opposite pyrrole targets the G-C bp, and pyrrole-imidazole targets the C-G bp. Pyrrole-pyrrole degenerately targets the T-A bp and A-T bp.[10] We have reported previously that PI polyamide targeted to the transforming growth factor-β1 promoter for progressive renal diseases significantly inhibited the transforming growth factor-β1 promoter activity and the expressions of transforming growth factor-β1 mRNA and protein in mesangial cells.[13] These findings suggest that the synthetic PI polyamides targeting gene promoter may, therefore, be feasible agents for the treatment of such diseases.

In this study, to develop a new agent for the treatment of restenosis after angioplasty, we designed a PI polyamide targeting rat LOX-1 gene promoter (PI polyamide to LOX-1) and examined its effects on LOX-1 expression and neointimal formation after balloon arterial injury in a rat model.

Methods

Synthesis of Polyamide Targeting Rat LOX-1

PI polyamide to LOX-1 was designed to span the boundary of the activator protein-1 (AP-1) binding site (−63 to −58) of the LOX-1 promoter (Figure 1A and 1B). A mismatch polyamide was used as a negative control; it was designed not to bind transcription binding sites of the promoter (Figure 1C). PI polyamides were synthesized by Gentier Biosystems Inc, according to methods described previously.[14]

Cell Culture

Rat aortic endothelial cells (Cell Applications) were inoculated on the coated plate and cultured in rat endothelial cell growth medium containing heparin, hydrocortisone, human epidermal growth factor, human fibroblast growth factor, dibutyryl cAMP, and FBS (5% vol/vol final concentration) in a CO_2 incubator. After reaching 90% confluence, the endothelial cells were incubated in serum-free medium for 24 hours, and then the medium was exchanged for a new medium at the start of the experiments.

Reverse Transcription and PCR Analysis

The total RNA was isolated and reverse transcribed as described previously.[15] The primers used to amplify monocyte chemoattractant protein-1 (MCP-1), matrix metallopeptidase-9 (MMP-9), and adhesion molecule-1 (ICAM-1) are listed in Table S1 (available online at http://hyper.ahajournals.org.). 18S ribosomal RNA was amplified as an internal control. PCR was performed according to the profiles shown in Table S2. PCR was performed in a DNA thermal cycler (GeneAmp PCR System 2700, Applied Biosystems). The quality and concentration of the amplified PCR products were determined using an Agilent 2100 Bioanalyzer (Agilent).

Arterial Injury and Treatment With Polyamide

This study confirmed to the standards of the Guide for the Care and Use of Laboratory Animals published by the National Institutes of Health. Male Wistar rats (Charles River Breeding Laboratories) weighing 300 to 350 g were used in all of the experiments. The rats were anesthetized by an IP injection of pentobarbital (100 mg/kg of body weight). The left carotid artery was isolated, and a Fogarty 2F embolectomy catheter (Baxter Healthcare) was introduced through the external carotid arteriotomy incision, advanced to the aortic arch, inflated to produce moderate resistance, and then gradually withdrawn 3 times to produce a distending and de-endothelializing injury.[16] The catheter was removed and the external carotid branch ligated. For local delivery, PI polyamide to LOX-1 or mismatch polyamide was diluted to 10 or 100 μg in 50 μL of saline, and they were injected and maintained in the artery for 10 minutes. After the incubation period, the solution was evacuated, the artery was washed with PBS 3 times, and then the blood flow through the common carotid artery was re-established.

Distribution of Fluorescein-Labeled Polyamide in Injured Artery

To assess the distribution of the polyamide in the carotid artery after the balloon injury, 100 μg of fluorescein isothiocyanate (FITC)–labeled PI polyamide to LOX-1 was incubated within the lumen of the artery for 10 minutes. The vessels were harvested 30 minutes, 2 hours and 24 hours later. Frozen specimens were made and then examined by fluorescence microscopy.

Morphometric Analysis of Neointimal Hyperplasia

The effect of polyamide on neointimal formation was measured as described previously.[17] The rats were euthanized by a lethal injection of sodium pentobarbital (IP, 100 mg/kg of body weight) at 21 days after balloon injury and then perfused with saline followed by 10% formalin at physiological pressure. For immunohistochemistry and a morphometric analysis, the arteries were fixed in 100% methanol overnight, and the middle one third of the common carotid artery was then cut into 4 segments and embedded in paraffin. The specimens were cross-sectioned at a thickness of 3 μm and stained with hematoxylin-eosin. The intima/media cross-sectional area ratios were determined using a computerized apparatus and the National Institutes of Health Image software program (version 1.57).

Immunohistochemistry

Paraffin blocks of the segments of the carotid arteries were used for the immunohistochemistry assay. LOX-1 expression was identified

with goat polyclonal anti–LOX-1 antibody (1:200, Santa Cruz), and incubated with fluorescein-conjugated chicken antigoat antibody (1:500, Invitrogen). After washing with PBS, the sections were incubated with Hoechst 33342 and then viewed by a laser scanning confocal imaging system.

Statistical Analyses

The values are reported as the means±SEMs. Student *t* test was used for unpaired data. Two-way ANOVA was also used. $P<0.05$ was considered to be statistically significant.

Results

Rat LOX-1 Promoter Activity

To identify DNA elements for regulation of rat LOX-1 promoter activation, 4 deletion constructs of the rat LOX-1 promoter were generated (Figure S1A). These constructs were transiently transfected into HEK-293 cells treated without or with phorbol 12-myristate 13-acetate (PMA) and measured for luciferase activity. PMA-induced activity was observed in −2385Luc, −1978Luc, −1323Luc, and −128Luc. The luciferase activity of these constructs significantly ($P<0.05$) increased with PMA by 2.8- to 3.2-fold in comparison with the basal activity, whereas the promoterless construct pGL3-basic was unresponsive. These results indicate that the sequence from −128 to +24 is important for PMA-induced activation of the LOX-1 promoter. We searched for transcription factor–binding sites with TFSEARCH and found an AP-1 site (5′-TGAGTCA-3′) lying between bp −59 and −53. To further confirm this AP-1 site on the LOX-1 promoter necessary for LOX-1 promoter activity in response to PMA, a 2-bp mutated construct was made in the luciferase reporter plasmid −128Luc. The luciferase activity in the HEK-293 cells transfected with these mutants revealed that mutation of the AP-1 site abolished the effect of PMA on LOX-1 promoter activity (Figure S1B). Therefore, this AP-1 site was essential for promoter activation. The PI polyamide to LOX-1 was then designed to interfere with this site.

Binding of Polyamide to Target DNA

The binding affinity and specificity of polyamide to target DNA were determined by gel shift assay (Figure S2). PI polyamide to LOX-1 bound the target double-stranded DNA. However, PI polyamide to LOX-1 did not bind to the 2-bp mutated double-stranded DNA. The mismatch polyamide did not bind to the double-stranded DNA.

Effect of PI Polyamide to LOX-1 on LOX-1 Promoter Activity

PMA (0.1 μmol/L) markedly increased the luciferase activity in HEK-293 cells transfected with LOX-1 promoter plasmid.

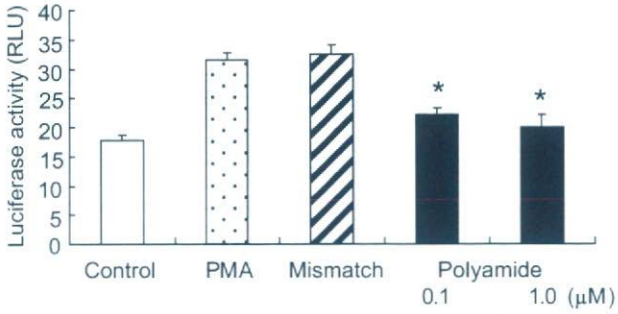

Figure 2. The effect of PI polyamide targeting rat LOX-1 promoter (PI polyamide to LOX-1) on the LOX-1 promoter activity. HEK-293 cells were transfected with recombinant LOX-1 promoter plasmids; 24 hours after transfection, cells were incubated with either PI polyamide or mismatch polyamide in the presence or absence of 0.1 μmol/L of PMA; thereafter, the luciferase activity in the cell extracts was determined. The data are the means±SEMs (n=8). *$P<0.05$ vs treatment with PMA.

Treatment consisting of 0.1 and 1.0 μmol/L of PI polyamide to LOX-1 significantly ($P<0.05$) inhibited the LOX-1 promoter activity. However, the mismatch polyamide (1 μmol/L) did not affect the LOX-1 promoter activity (Figure 2).

Effect of PI Polyamide to LOX-1 on the Expressions of LOX-1 mRNA and Protein in Cultured Rat Endothelial Cells

The expression of LOX-1 mRNA and protein was significantly ($P<0.05$) increased with PMA. PI polyamide to LOX-1 significantly ($P<0.05$) decreased the amount of LOX-1 mRNA and protein. However, the mismatch polyamide did not affect the amount of LOX-1 mRNA and protein (Figure S3A and S3B).

Distribution of PI Polyamide to LOX-1 in Injured Artery

Figure 3 shows the distribution of FITC-labeled PI polyamide to LOX-1 in rat carotid artery after balloon injury. The FITC-labeled PI polyamide was not seen and then was uptaken into the entire wall of the injured artery at 30 minutes after injury. Thereafter, the FITC-labeled PI polyamide remained and strongly localized in the nuclei of midlayer smooth muscle by 24 hours.

Effect of PI Polyamide to LOX-1 on Neointimal Thickening

Figure 4 shows the effect of PI polyamide to LOX-1 on neointimal thickening in rat carotid artery at 21 days after balloon injury. Both 10 and 100 μg of PI polyamide to

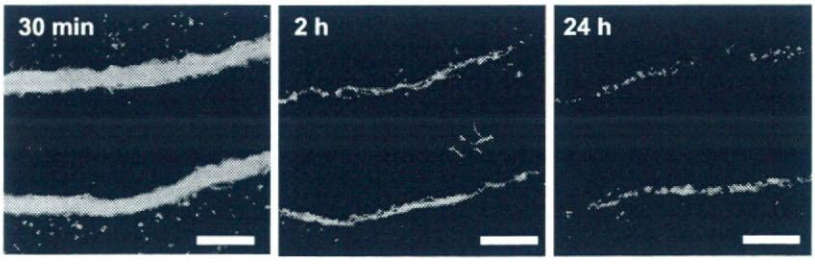

Figure 3. Distribution of FITC-labeled PI polyamide targeting rat LOX-1 promoter (PI polyamide to LOX-1) in injured carotid artery. FITC-labeled polyamide (100 μg) was incubated within the lumen of artery for 10 minutes. The vessels were harvested 30 minutes, 2 hours, or 24 hours later and frozen specimens were made and were examined by fluorescence microscopy. Scale bar represents 1 mm.

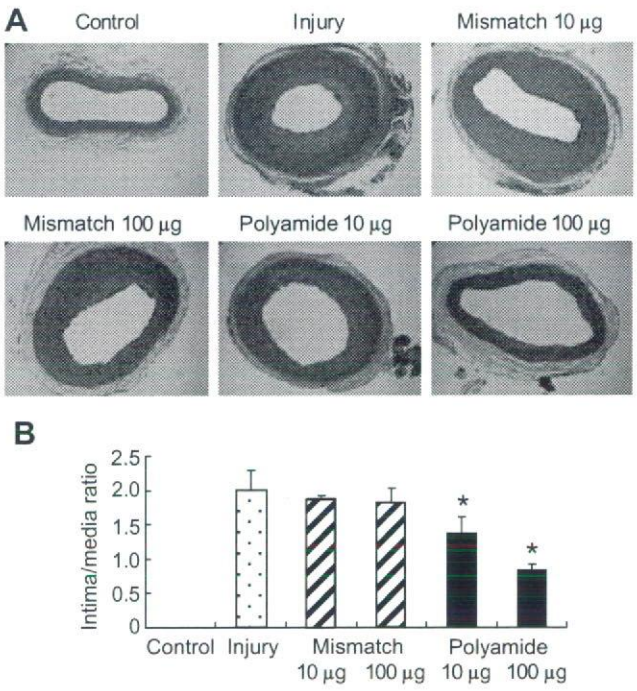

Figure 4. The effect of PI polyamide to LOX-1 on neointimal hyperplasia in rat carotid arteries at 21 days after injury. A, Hematoxylin-eosin staining of a cross section of the specimens treated without or with polyamide or mismatch polyamide. B, Intimal and medial cross-sectional areas of the arteries were determined with a computerized apparatus and National Institutes of Health Image software program. The data are the means±SEMs (n=4). *$P<0.05$ vs injury. Magnification: ×100.

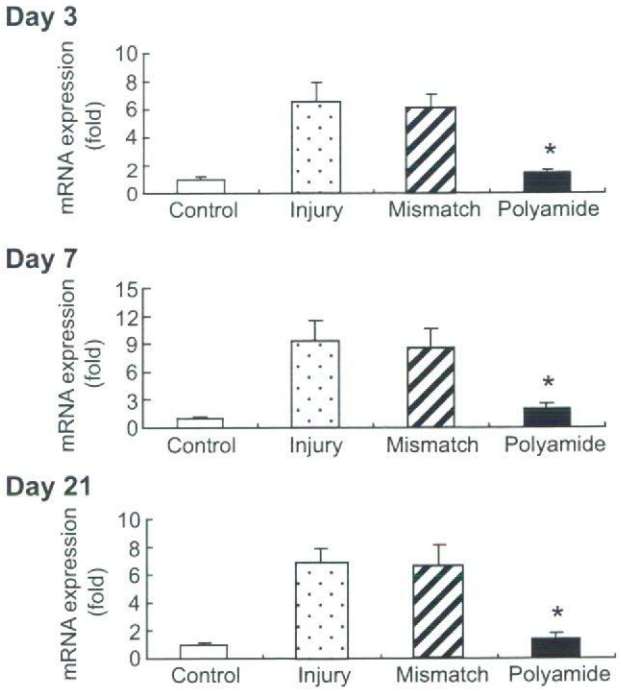

Figure 5. The effect of PI polyamide targeting rat LOX-1 promoter (PI polyamide) on the expression of LOX-1 mRNAs in rat carotid artery after balloon injury. A 2F embelectomy catheter with balloon was drawn toward the arteriotomy site 3 times. At 3, 7, and 21 days after the injury, arteries were incubated without (Injury) or with 100 μg of PI polyamide to LOX-1 (Polyamide) or mismatch polyamide (Mismatch) for 10 minutes. Total RNA was extracted, and LOX-1 mRNAs were evaluated by real-time PCR assay. The data are the ratios of LOX-1 to GAPDH mRNA abundances (means±SEMs; n=4). * $P<0.05$ vs injury.

LOX-1 significantly ($P<0.05$) reduced neointimal thickening by 31% and 58%, respectively, in comparison with the injury group. The mismatch polyamide did not affect the neointimal formation.

Effect of PI Polyamide to LOX-1 on Expression of LOX-1 in the Injured Artery

The expression of LOX-1 mRNA was significantly ($P<0.05$) higher in the injured artery than that in the noninjured artery. Treatments with PI polyamide to LOX-1 significantly ($P<0.05$) reduced the expression of LOX-1 mRNA in the artery at 3, 7, and 21 days after balloon injury. The treatments with mismatch polyamide did not affect the expression of LOX-1 mRNA in the artery (Figure 5). Immunofluorescence staining showed that LOX-1 was not detectable in the noninjured artery, whereas LOX-1 was markedly increased in the endothelial layer and midlayer smooth muscle in the injured artery at 21 days after injury. The treatment of PI polyamide to LOX-1 reduced the LOX-1 expression. The mismatch polyamide did not affect the expression of LOX-1 (Figure 6).

Effect of PI Polyamide to LOX-1 on Re-endothelialization in the Injured Artery

Immunohistochemistry of endothelial cells with anti–von Willebrand factor antibody in rat carotid artery at 21 days after balloon injury showed that endothelial cells were stained in the intimal surface after balloon injury. The treatment of PI polyamide to LOX-1 obviously enhanced the staining of the endothelial cells in the injured artery (Figure 6).

Effect of PI Polyamide to LOX-1 on the Expression of MCP-1, ICAM-1, and MMP-9 mRNAs in Injured Artery

The expression of MCP-1, ICAM-1, and MMP-9 mRNAs significantly ($P<0.05$) increased in the injured artery 3 days after injury in comparison with the noninjured artery. The treatment of PI polyamide to LOX-1 significantly ($P<0.05$) reduced the expression of these mRNAs. The mismatch polyamide did not affect the expression of these mRNAs (Figure 7).

Discussion

In the present study, we constructed deletion mutants and analyzed the rat LOX-1 promoter activity stimulated by PMA and found a transcription factor AP-1 binding site between bp −59 and −53 in the rat LOX-1 promoter. The site-directed mutation analysis further confirmed this positive regulatory element for the activation of LOX-1 promoter. These findings imply that, to interfere with this AP-1 binding site, PI polyamide to LOX-1 will suppress the LOX-1 gene activation and expression. For gene-specific targeting, the polyamide was then designed to target the sequence immediately adjacent to the binding site for AP-1 on the promoter. Synthetic PI polyamides have been shown to be cell permeable and able to

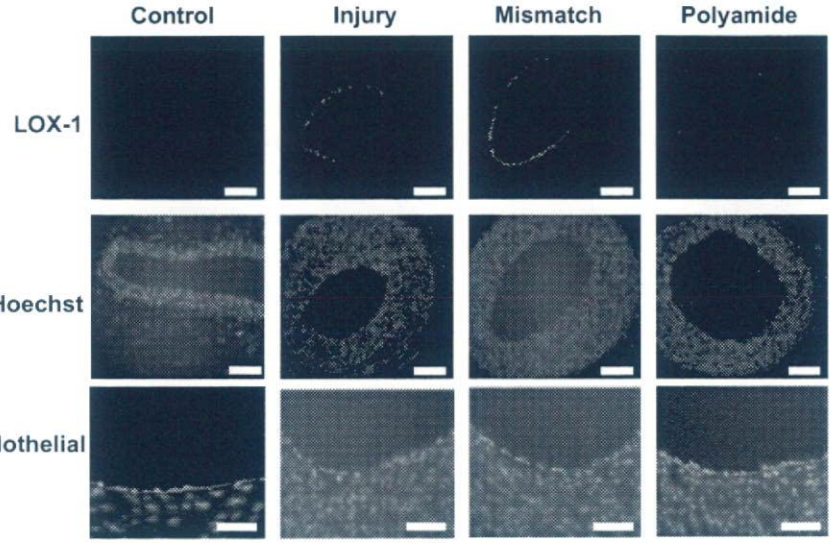

Figure 6. Effect of PI polyamide targeting rat LOX-1 promoter (PI polyamide to LOX-1) on the expression of LOX-1 protein and the re-endothelialization of rat carotid artery after balloon injury. A 2F embelectomy catheter with balloon was drawn toward the arteriotomy site 3 times. After the injury, arteries were incubated without (Injury) or with 100 μg of PI polyamide to LOX-1 (Polyamide) or mismatch polyamide (Mismatch) for 10 minutes. At 21 days after balloon injury the carotid arteries were removed and stained with anti–LOX-1 antibody (LOX-1) or anti–von Willebrand factor antibody (Endothelial cell), and incubated with fluorescein-conjugated respective secondary antibodies. The nuclei were stained with Hoechst 33342. Scale bar represents 200 μm for LOX-1 and Hoechst or 50 μm for endothelial cell.

inhibit the transcription of specific genes.[18] In our previous study, we also demonstrated that synthetic PI polyamides easily passed into the cells and then entered the nuclei of cells without any vector or delivery reagents to inhibit the expression of the target gene.[8,13] In this study, in a construct of plasmid, the polyamide significantly inhibited the LOX-1 promoter activity stimulated with PMA, thus suggesting that the synthetic PI polyamide to LOX-1 actually interfered with the AP-1 transcription factor-DNA interaction.

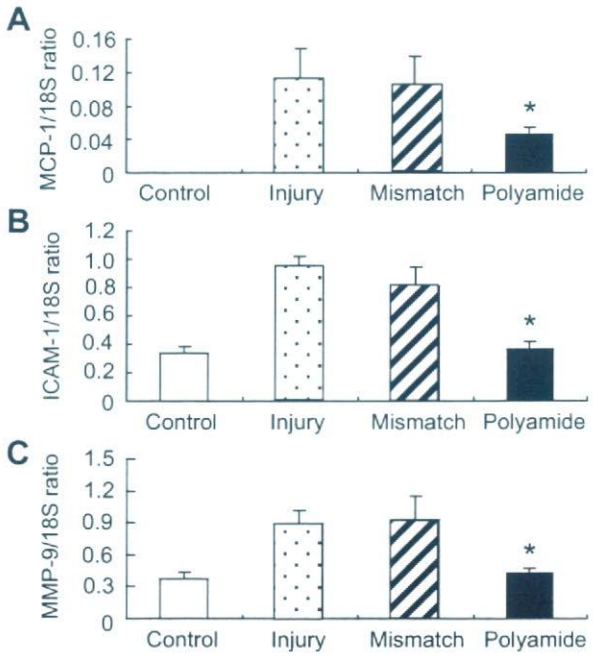

Figure 7. Effect of PI polyamide targeting rat LOX-1 promoter (PI polyamide to LOX-1) on the expression of MCP-1, ICAM-1, and MMP-9 mRNAs in rat carotid artery after balloon injury. A 2F embelectomy catheter with balloon was drawn toward the arteriotomy site 3 times. After the injury, arteries were incubated without (Injury) or with 100 μg of PI polyamide to LOX-1 (Polyamide) or a mismatch polyamide (Mismatch) for 10 minutes. At 3 days after balloon injury, total RNA was extracted and mRNA expression was evaluated by RT-PCR assay. The ratio of mRNA to 18S rRNA was evaluated. The data are the means±SEMs (n=4 to 6). *$P<0.05$ vs injury.

The designed PI polyamide to LOX-1 significantly inhibited the expression of LOX-1 mRNA and protein stimulated with PMA in cultured rat aortic endothelial cells, thus suggesting that PI polyamide to LOX-1 has the potential to control LOX-1 gene expression. LOX-1 has been reported to induce apoptosis of endothelial cells, which is associated with the atherosclerosis and restenosis of artery.[7,19] Because the endothelium has the ability to improve arterial injury, the denudation of the endothelium by coronary intervention may, thus, accelerate the occurrence of restenosis. Drug-eluting stents (DESs) have been shown to be effective for preventing in-stent restenosis. The sirolimus-coated DESs can prevent in-stent restenosis by inducing the complete inhibition of vascular smooth muscle cell hyperplasia by its effect on cell cycle arrest.[20] However, complications such as subacute thrombosis or late thrombosis have been reported recently in patients implanted with a sirolimus-coated DES.[21] Sirolimus prevents re-endothelialization of the inner side of the metal stent, which may cause late thrombosis. These complications have led to the development of second-generation DESs that do not induce late thrombosis. In the present study, the rapid regeneration of endothelial cells may appear to contribute to the suppression of intimal hyperplasia after treatment with PI polyamide to LOX-1. The preservation of the endothelium by PI polyamide to LOX-1 is, thus, considered to be very advantageous for DESs to prevent both restenosis and late thrombosis.

In the present study, FITC-labeled PI polyamide to LOX-1 was well distributed into the wall of the carotid artery and strongly bound the cell nucleus without any vectors after injury. Nucleic acid medicines, such as antisense DNA, ribozymes, and decoy, have been developed as gene-silencing agents. Decoys, in particular, inhibit the binding of target transcription factors in a manner similar to polyamides. However, because these agents tend to easily degrade when coming into contact with nucleases, they require drug-delivery systems for sufficient distribution into organs. In contrast, PI polyamides are completely resistant to nucleases and can be delivered into organs without delivery systems.

In the present study, the expression of LOX-1 was low in the noninjury artery, whereas the expression of LOX-1 was significantly increased after balloon injury. PI polyamide to LOX-1 effectively inhibited LOX-1 expression in the injured artery and attenuated the neointimal formation of the artery after injury. LOX-1 has been reported to be expressed in atheromatous lesions and is involved in neointimal hyperplasia after vascular injury.[7] Therefore, LOX-1 is a target for the treatment of restenosis, and the polyamide against LOX-1 may be an effective approach to inhibit restenosis.

LOX-1 is a main receptor for ox-LDL. Ox-LDL plays a role in the initiation and progression of atherosclerosis via LOX-1.[22] Other than ox-LDL, LOX-1 binds multiple classes of ligands that are implicated in the pathogenesis of atherosclerosis by the apoptosis of cells and the activation of platelets.[23] A significant number of apoptotic cells have been reported to be present in restenotic lesions after balloon injury,[24] thus implying that several factors presented after arterial injury may interact with and activate LOX-1. The activation of LOX-1 may, therefore, increase superoxide generation, reduce the production of NO, induce MCP-1, and increase leukocyte adhesiveness.[25] Hinagata et al[7] demonstrated that the inhibition of LOX-1 with anti–LOX-1 antibody attenuated oxidative stress in the neointima of the rat injured artery. In addition, antioxidative agents have been reported to inhibit the neointimal hyperplasia in normocholesterolemic rabbits and pigs.[26] In the present study, the expression of MCP-1, ICAM-1, and MMP-9 mRNAs was markedly increased in the injured artery, which was significantly decreased with treatments of PI polyamide to LOX-1, suggesting that increases in these molecules are associated with the induction of LOX-1 in the injured artery. MCP-1 is a potent chemotactic factor of monocytes[25] and is produced by activated vascular smooth muscle cells or other type of cells.[27] Antisense oligodeoxynucleotides to LOX-1 inhibit MCP-1 and monocyte adhesion.[28] The inhibition of MCP-1 results in a significant attenuation of neointimal hyperplasia.[29] MMP-9 is upregulated after angioplasty and involved in regulating the proliferation and migration of vascular smooth muscle cells, which are crucial steps for intimal hyperplasia.[30] Therefore, the designed PI polyamide to LOX-1 may attenuate intimal hyperplasia through cellular adhesion to the injured artery. This might partially explain the beneficial effects of the PI polyamide targeting LOX-1 on the suppression of neointimal hyperplasia.

In conclusion, the synthetic PI polyamide to LOX-1 potentially suppressed the LOX-1 promoter activity. PI polyamide to LOX-1 was delivered in midlayer smooth muscle of an injured artery without delivery reagents and significantly inhibited the intimal hyperplasia with the downregulation of MCP-1, ICAM-1, and MMP-9 and re-endothelialization in the injured artery. PI polyamide to LOX-1 is a potentially effective agent for the treatment of in-stent restenosis and will be a candidate agent for the development of next-generation DES.

Perspectives

Because polyamides can be readily designed and synthesized to target any gene, they are, therefore, expected to become important gene-silencing agents in the postgenome era. PI polyamide to LOX-1 is, therefore, considered to be a feasible gene silencing agent for the prevention of in-stent restenosis of the coronary artery as a next generation agent for DES.

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Disclosures

None.

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