High-Glucose–Induced Upregulation of Osteopontin Is Mediated via Rho/Rho Kinase Pathway in Cultured Rat Aortic Smooth Muscle Cells

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Objective—Osteopontin is upregulated in the diabetic vascular wall and in vascular smooth muscle cells cultured under high glucose concentration. In the present study, we analyzed the mechanism of high-glucose–induced upregulation of osteopontin in cultured rat aortic smooth muscle cells.

Methods and Results—We found that an inhibitor of Rho-associated protein kinase, Y-27632, suppressed osteopontin mRNA expression under high glucose concentration. Transfection of cells with a constitutive active Rho mutant, pSRα-myc-RhoDA, enhanced osteopontin mRNA expression. Furthermore, incubation of cells under high glucose concentration activated Rho, indicating that Rho/Rho kinase pathway mediates high-glucose–stimulated osteopontin expression. Treatment of cells with an inhibitor of protein kinase C, GF109203X, and azaserine, an inhibitor of the hexosamine pathway, suppressed high-glucose–induced Rho activation. Glucosamine treatment was shown to activate Rho. Treatment of cells with an inhibitor of MEK1, PD98059, suppressed osteopontin mRNA expression under high glucose concentration. Incubation of cells under high glucose concentration activated ERK. Finally, transfection of cells with pSRα-myc-RhoDA also activated ERK.

Conclusions—in conclusion, our present findings support a notion that Rho/Rho kinase pathway functions downstream of protein kinase C and the hexosamine pathways and upstream of ERK in mediating high-glucose–induced upregulation of osteopontin expression. (Arterioscler Thromb Vasc Biol. 2004;24:1-6.)

Key Words: osteopontin • Rho • glucose • atherosclerosis • smooth muscle cells

Osteopontin (OPN) is a multifunctional phosphoprotein secreted by many cell types such as osteoclasts, lymphocytes, macrophages, epithelial cells, and vascular smooth muscle cells (SMC). Overexpression of OPN has been found in several physiological and pathological conditions, including immunologic disorders, neoplastic transformation, progression of metastasis, formation of urinary stones, and wound healing.

It was reported that OPN protein and mRNA were expressed in the neointima and in calcified atherosomatous plaque. A neutralizing antibody against OPN was found to inhibit rat carotid neointimal formation after endothelial denudation. These results have suggested that OPN promotes the development of atherosclerosis. Recently, we found upregulation of OPN expression in human and rat diabetic vascular walls. It was also noted that high glucose concentrations stimulated OPN expression via a protein kinase C (PKC)-dependent pathway and the hexosamine pathway in cultured rat aortic SMC. Furthermore, OPN was found to stimulate migration and enhance platelet-derived growth factor-mediated DNA synthesis of cultured rat aortic SMC.

Based on these data, we suggest that OPN plays a role in accelerated atherogenesis in diabetes mellitus.

In the present study, we further analyzed the mechanism of high-glucose–induced upregulation of OPN in cultured rat aortic SMC. We show that Rho/Rho kinase pathway functions downstream of PKC and the hexosamine pathways and upstream of ERK in mediating high-glucose–stimulated OPN expression.

Methods

Reagents

GGTI-298, an inhibitor of geranylgeranyltransferase I, FTI-277, an inhibitor of farnesyltransferase, Y-27632, an inhibitor of Rho-associated protein kinase, GF109203X, an inhibitor of PKC, PD98059, an inhibitor of MEK1, SB203580, an inhibitor of p38 mitogen-activated protein (MAP) kinase, and SP600125, an inhibitor of c-Jun N-terminal kinase (JNK), were purchased from Calbiochem (La Jolla, CA). Azaserine, an inhibitor of glutamine:fructose-6-phosphate aminotransferase (GFAT) was from Sigma (St. Louis, MO). The p44/42 MAP kinase assay kit, p38 MAP kinase assay kit, and SAPK/JNK assay kit were from Cell Signaling Technology (Beverly, MA). Rho activation assay kit was from UBI (Lake Placid, NY).
to estimate the efficiency of RNA loaded in each lane, or from Dr Masaki Kitahara (Nissan Chemical, Saitama, Japan).

**Cell Culture**

Primary cultures of rat aortic SMC were isolated as described by the explant method from adult male Wistar rats weighing ~200 grams. Cells were maintained in Dulbecco modified Eagle medium containing 5.5 mmol/L glucose, 10% fetal bovine serum, and 40 µg/mL gentamycin (Schering-Plough, Kenilworth, NJ) in a humidified atmosphere at 37°C in 5% CO2. Cells at passages 7 to 9 were used for the present experiments.

**Transient Transfection**

At 50% confluency in 100-mm dishes, cells were transfected with pSR-myc-RhoDA by using FuGene 6 transfection reagent (Roche Molecular Biochemicals, Indianapolis, IN). pSR-myc-RhoDA was mixed with FuGene 6 transfection reagent at the ratio of 1:3 and incubated at room temperature for 15 to 40 minutes. Then, cells were transfected by incubation with the mixture for 24 hours. After additional 48 hours of incubation under normal glucose concentration (5.5 mmol/L glucose), cells were processed for Northern blotting and MAP kinase activity assays.

**Northern Blotting**

Subconfluent cells growing in 100-mm dishes were serum-starved for 24 hours and then incubated under different glucose concentrations for the indicated times. After phosphorylation reactions, samples were processed for Western blotting with phospho c-Jun antibody, according to manufacturer’s instructions.

**Results**

**Pitavastatin Suppresses OPN Expression Under High glucose Concentration**

Recently, we found upregulation of OPN expression in high-glucose–induced diabetic rats. Furthermore, oral administration of Pitavastatin, an HMG-CoA reductase inhibitor, effectively suppressed abnormally upregulated expression of OPN mRNA in the aorta and kidney of streptozotocin-induced diabetic rats. These findings prompted us to examine in vitro effect of Pitavastatin on high-glucose–induced upregulation of OPN expression in cultured rat aortic SMC. Cells were incubated with different concentrations of Pitavastatin at 37°C for 48 hours under high glucose concentration (30 mmol/L glucose). After incubation, the cells were processed for Northern blotting. As shown in Figure 1A, Pitavastatin dose-dependently decreased OPN mRNA level.

Pitavastatin did not show cytotoxic effect at the examined doses as evaluated by trypan blue dye exclusion assay (data not shown).

**Isoprenylation Is Required for OPN Expression**

Inhibition of HMG-CoA reductase prevents the biosynthesis of isoprenoids, such as geranylgeranylpyrophosphate and farnesylpyrophosphate, and thereby inhibits subsequent isoprenylation. It is thus conceivable that the observed effect of Pitavastatin may result from inhibition of isoprenylation. To prove this assumption, we examined effects of inhibitors for geranylgeranyltransferase I and farnesyltransferase, GGTI-298 and FTI-277, respectively, on high-glucose–induced upregulation of OPN expression in cultured rat aortic SMC. As shown in Figure 1B and C, GGTI-298 and FTI-277 dose-dependently decreased OPN mRNA level under high glucose concentration, as expected.
Rho/Rho Kinase Pathway Mediates
High-Glucose–Induced Upregulation of
OPN Expression

It is well known that geranylgeranylation is prerequisite for Rho, a small GTP-binding protein, to exert its cellular function. Therefore, Rho seemed to be a possible candidate involved in mediating a positive signal for OPN expression.

To evaluate a role of Rho, we first examined effect of an inhibitor of Rho-associated protein kinase, Y-27632, on high-glucose–induced upregulation of OPN expression in cultured rat aortic SMC. As shown in Figure 2A, Y-27632 dose-dependently decreased OPN mRNA level under high-glucose conditions. Data shown in this figure are representative of at least 2 independent experiments providing essentially similar results.

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glucose concentration, suggesting a critical role of Rho kinase activity in OPN expression.

Next, we examined the effect of transient transfection of a constitutively active Rho mutant, pSRα-myc-RhoDA, on OPN expression in cultured rat aortic SMC. As shown in Figure 2B, transfection of pSRα-myc-RhoDA enhanced OPN mRNA expression in proportion to the efficiency of its transfection, confirming that Rho mediates a positive signal for OPN expression.

Finally, we examined the effect of high glucose on Rho activation in cultured rat aortic SMC. As shown in Figure 2C, the amount of GTP-Rho in cells cultured in 30 mmol/L glucose was found to be much higher than that in 5.5 mmol/L glucose. No difference was found in total Rho protein levels between 5.5 mmol/L glucose and 30 mmol/L glucose (data not shown). In contrast, treatment of cells with osmotic controls (5.5 mmol/L D-glucose plus 24.5 mmol/L L-glucose or 5.5 mmol/L D-glucose plus 24.5 mmol/L D-mannitol) providing an equivalent osmolarity as 30 mmol/L glucose, did not change Rho activity (data not shown), indicating that the observed enhanced effect on Rho activity is specific to glucose. Taken together, these data strongly support a notion that Rho/Rho kinase pathway mediates high-glucose--induced upregulation of OPN expression.

Rho/Rho Kinase Pathway Is a Common Downstream of PKC and Hexosamine Pathways

It was previously noted that high glucose concentrations stimulated OPN expression via a PKC-dependent pathway and the hexosamine pathway in cultured rat aortic SMC. Therefore, our next question was whether Rho/Rho kinase pathway functions downstream of these pathways. As shown in Figure 3A, treatment of cells with GF109203X, an inhibitor of PKC, dose-dependently inhibited high-glucose--stimulated increase in Rho activity, suggesting the involvement of PKC activation in the process. Likewise, treatment with azaserine, an inhibitor of GFAT, the key enzyme of the hexosamine pathway, dose-dependently inhibited high-glucose--stimulated increase in Rho activity. Total Rho protein levels were unchanged by addition of high glucose, 1 μM GF109203X or 5 μmol/L azaserine (data not shown). Furthermore, as shown in Figure 3B, glucosamine dose-dependently enhanced Rho activity. These data also suggest the involvement of the hexosamine pathway in the process.

ERK Functions Downstream of Rho in Mediating High-Glucose--Induced Upregulation of OPN Expression

Small GTP-binding proteins have been demonstrated to induce a variety of responses, including activation of MAP kinase cascades in various cells. Therefore, to trace a signal-
After serum-starvation for 24 hours, cells were incubated with the indicated concentrations of PD98059, SB203580, or SP600125 in serum-free medium containing 30 mmol/L glucose for 48 hours. After incubation, cells were processed for Northern blotting as described in the legend to Figure 1. B, High-glucose-induced ERK activation in cultured rat aortic SMC. After serum-starvation for 24 hours, cells were incubated in serum-free medium containing either 5.5 mmol/L or 30 mmol/L glucose for 24 to 48 hours. After incubation, activities of ERK1/2 and p38 MAP kinase in cell lysates were measured by immune complex kinase assay with an immobilized phospho p44/42 MAP kinase antibody and Elk-1 protein as substrate, or with an immobilized phospho p38 MAP kinase antibody and ATF-2 protein as substrate, respectively. After phosphorylation reactions, samples were processed for Western blotting with phospho Elk-1 antibody or phospho ATF-2 antibody. Data are expressed as fold increase relative to the value obtained in 5.5 mmol/L glucose at the indicated times. C, Effect of transient transfection of a constitutive active Rho mutant (CA Rho) on activation of MAP kinases in cultured rat aortic SMC. Cells were transfected with 3 μg of pSRα-myc-RhoDA and incubated for 48 hours as described in the legend to Figure 2. After incubation, MAP kinase activities in cell lysates were determined. Data are expressed as fold increase relative to the value obtained in the absence of CA Rho. Double bands in the JNK activity assay correspond to 37- and 35-kilodalton forms of phosphorylated c-Jun fusion proteins. Data shown in this figure are representative of at least 2 independent experiments providing essentially similar results.

Discussion
In the present study, we demonstrate that Rho/Rho kinase pathway functions downstream of PKC and the hexosamine pathways and upstream of ERK in mediating high-glucose–induced upregulation of OPN expression. Involvement of Rho in mediating a positive signal for OPN expression has also been reported by Chaulet et al. They showed that extracellular UTP increased OPN expression in cultured rat aortic SMC and thereby induced migration of the cells. Blockade of ERK1/2 or Rho pathways led to the inhibition of UTP-induced OPN increase and migration, demonstrating the central role of OPN in this process. The finding, together with our present observation, underscores the importance of Rho in OPN expression.

Our present finding that high glucose induces Rho activation sheds new light on the mechanism of the accelerated atherogenesis in diabetes mellitus, because involvement of Rho/Rho kinase pathway has been implicated in a wide variety of atherosclerotic processes, including neointimal formation, vasovasodilatory response, proliferation, migration, and anti-apoptosis of vascular SMC, and vascular gene expression of monocyte chemoattractant protein-1, transforming growth factor-β1, and inducible nitric oxide synthase. Besides our present study using rat aortic SMC, high-glucose–induced Rho activation was also observed in cultured rat mesangial cells and in basilar artery derived from streptozotocin-induced diabetic rats. It is thus conceivable that high glucose promotes diabetic vascular complications not only by upregulation of OPN but also by more diverse effects resulting from Rho activation.

It was reported that transfection of vascular SMC with the c-Ha-rasEJ oncogene induced overexpression of OPN. It is
well known that farnesylation is prerequisite for Ras to exert its cellular effect; therefore, our present finding that the inhibitor of farnesyltransferase, FTI-277, suppressed OPN expression might be ascribed to the inhibition of Ras function by the drug. In our previous study, however, the inhibitory effect of Pitavastatin on OPN expression in cultured rat aortic SMC was almost completely reversed by the addition of mevalonate or geranylgeranylpyrophosphate but not by farnesylation. Studies using other types of cells, fibroblasts, or keratinocytes showed that transfection of dominant-negative Rho or dominant-negative Rac suppressed Rac-induced activation of Raf-MEK-ERK pathway, indicating that Ras requires either Rho or Rac function in activation of Raf-MEK-ERK pathway. Based on these findings, it is speculated that the inability of farnesylpyrophosphate to rescue the cells from the inhibition of OPN expression by Pitavastatin might be caused by suppression of Rho family function in Pitavastatin-treated cells. Further study is necessary to prove this possibility.

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References
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