0026-895X/06/7001-415–425$20.00
MOLECULAR PHARMACOLOGY
Copyright © 2006 The American Society for Pharmacology and Experimental Therapeutics
Mol Pharmacol 70:415–425, 2006

Vol. 70, No. 1
22954/3121621
Printed in U.S.A.

Peroxisome Proliferator-Activated Receptor-γ and Retinoic Acid X Receptor α Represses the *TGFβ1* Gene via PTEN-Mediated p70 Ribosomal S6 Kinase-1 Inhibition: Role for Zf9 Dephosphorylation[S]

Seung Jin Lee, Eun Kyoung Yang, and Sang Geon Kim

National Research Laboratory, College of Pharmacy and Research Institute of Pharmaceutical Sciences, Seoul National University, Seoul, Korea

Received January 26, 2006; accepted April 11, 2006

ABSTRACT

Peroxisome proliferator-activated receptor (PPAR)-γ and retinoic acid X receptor (RXR) heterodimer regulates cell growth and differentiation. Zinc finger transcription factor-9 (Zf9), whose phosphorylation promotes target genes, is a transcription factor essential for transactivation of the *transforming growth factor (TGF)-β1* gene. This study investigated whether activation of PPARγ-RXR heterodimer inhibits *TGFβ1* gene transcription and Zf9 phosphorylation and, if so, what signaling pathway regulates it. Either 15-deoxy-δ(12,14)-prostaglandin J_2 (PGJ_2) or 9-*cis*-retinoic acid (RA) treatment decreased the TGFβ1 mRNA level in L929 fibroblasts. PGJ_2 + RA, compared with individual treatment alone, synergistically inhibited the *TGFβ1* gene expression, which was abrogated by PPARγ antagonists. Likewise, PGJ_2 + RA decreased luciferase expression from the *TGFβ1* gene promoter. Promoter deletion analysis of the *TGFβ1* gene revealed that pGL3-323 making up to −323-base pair region, but lacking PPAR-responsive elements, responded to PGJ_2 + RA. PGJ_2 + RA treatment inhibited the activity of p70 ribosomal S6 kinase-1 (S6K1), abolishing Zf9 phosphorylation at serine as did rapamycin [a mammalian target of rapamycin (mTOR) inhibitor]. Zf9 dephosphorylation by PGJ_2 + RA was reversed by transfection of cells with the plasmid encoding constitutively active S6K1 (CA-S6K1). Transfection with dominant negative S6K1 inhibited the *TGFβ1* gene. *TGFβ1* gene repression by PGJ_2 + RA was consistently antagonized by CA-S6K1. Ectopic expression of PPARγ1 and RXRα repressed pGL3-323 transactivation with S6K1 inhibition, which was abrogated by CA-S6K1 transfection. PGJ_2 + RA induced phosphatase and tensin homolog deleted on chromosome 10 (PTEN), whose overexpression repressed the *TGFβ1* gene through S6K1 inhibition, decreasing extracellular signal-regulated kinase 1/2–90-kDa ribosomal S6 kinase 1 and Akt-mTOR phosphorylations. Data indicate that activation of PPARγ-RXR heterodimer represses the *TGFβ1* gene and induces Zf9 dephosphorylation via PTEN-mediated S6K1 inhibition, providing insight into pharmacological manipulation of the *TGFβ1* gene regulation.

The human transforming growth factor-β isoforms constitute extracellular signaling molecules that have antiproliferative effects on mammalian cells, promoting the expression of cell adhesion molecules and extracellular matrix proteins. In particular, transforming growth factor (TGF)-β1 serves as a key fibrogenic mediator that can enhance extracellular matrix deposition and inhibit collagenase activity during fibrogenesis (Friedman, 1993). The regulation of TGFβ1 expression is complex and occurs at multiple levels, orchestrated transcriptionally by the multiple transcription factors and post-translationally by maturation of the precursors bound with TGFβ1 binding proteins (Kim et al., 1989a; Oklu and Hesketh, 2000).

The peroxisome proliferator-activated receptors (PPARs) are transcription factors that are members of the nuclear

This work was supported by National Research Laboratory Program (2001–2006), Korea Science and Engineering Foundation, The Ministry of Education, and Human Resources Development, South Korea.

[S] The online version of this article (available at http://molpharm.aspetjournals.org) contains supplemental material.

Article, publication date, and citation information can be found at http://molpharm.aspetjournals.org.
doi:10.1124/mol.106.022954.

ABBREVIATIONS: TGFβ1, transforming growth factor; PPAR, peroxisome proliferator-activated receptor; RXR, retinoic acid X receptor; PPRE, peroxisome proliferator-activated receptor response element; RA, 9-*cis*-retinoic acid; PGJ_2, 15-deoxy-δ(12,14)-prostaglandin J_2; AP-1, activator protein-1; S6K1, p70 ribosomal S6 kinase-1; PI3, phosphatidylinositol 3; mTOR, mammalian target of rapamycin; Zf9, zinc finger transcription factor-9; PTEN, phosphatase and tensin homolog deleted on chromosome 10; DN, dominant negative; CA, constitutively active; FBS, fetal bovine serum; RT-PCR, reverse transcription-polymerase chain reaction; bp, base pair(s); GAPDH, glyceraldehyde-3-phosphate dehydrogenase; PCR, polymerase chain reaction; BADGE, bisphenol A diglycidyl ether; ERK, extracellular signal-regulated kinase; RSK1, p90 ribosomal S6 kinase-1; GW9662, 2-chloro-5-nitrobenzanilide.

receptor superfamily (Dubuquoy et al., 2002). Among the PPAR subtypes, PPARγ is expressed in the major organs (Chawla et al., 1994). Treatment of animals with thiazolidinediones, synthetic PPARγ ligands, prevented early phase hepatic fibrogenesis caused by toxicants (Kon et al., 2002) and inhibited bile duct proliferation and fibrosis in animals with cholestasis (Marra et al., 2005). This paralleled the observation that thiazolidinediones inhibited hepatic stellate cell activation (Marra et al., 2000; Hazra et al., 2004). Thus, PPARγ is considered to be an important target for the prevention or treatment of fibrosis (Marra et al., 2000). The activated PPARγ by binding of ligand forms a heterodimer with RXRα and binds to specific PPAR response elements (PPREs) in the promoter region of its target genes (Kliewer et al., 1992), contributing to cell survival and differentiation (IJpenberg et al., 1997). 9-*cis*-Retinoic acid (RA) was identified as an activating ligand that is relatively selective for RXRα, which must heterodimerize with a permissive partner (Mukherjee et al., 1997). A previous study from this laboratory has shown that thiazolidinediones or 15-deoxy-δ(12,14)-prostaglandin J_2 (PGJ_2), when combined with RA at nanomolar levels, promotes PPRE-mediated gene transcription via activation of the PPARγ-RXR heterodimer (Park et al., 2004). RXR activation inhibited the *TGFβ1* gene by antagonizing activating protein-1 (AP-1) activity (Salbert et al., 1993). Nevertheless, the role of PPARγ-RXR heterodimer for *TGFβ1* gene regulation has never been studied.

p70 ribosomal S6 kinase-1 (S6K1), which is regulated by the phosphatidylinositol 3 (PI3)-kinase-mTOR pathway, plays as a multifunctional kinase for the phosphorylation of ribosomal S6 protein (Jeno et al., 1988), cAMP response element modulator (de Groot et al., 1994), BAD (Harada et al., 2001), and the eukaryotic elongation factor 2 kinase (Wang et al., 2001). Studies have shown that rapamycin inhibited liver fibrosis and TGFβ1 expression in rats bile duct-ligated or challenged with toxicants (Zhu et al., 1999; Biecker et al., 2005), accompanying decrease in S6K1 activity. Although S6K1 inhibition by an mTOR inhibitor has been shown to be implicated with antifibrosis, the role of S6K1 in *TGFβ1* gene regulation and the molecular mechanistic basis have not been elucidated.

Activation of zinc finger transcription factor-9 (Zf9), also named as KLF6, is critical in the induction of TGFβ1 during the activation of hepatic stellate cells (Ratziu et al., 1998). The *TGFβ1* gene contains the DNA response element interacting with Zf9 (Kim et al., 1989a). Zf9 also regulates TGFβ receptors and collagen α1(I), thereby promoting accumulation of extracellular matrix (Kim et al., 1998). Thus, Zf9 regulates multiple genes involved in tissue differentiation. In addition, Zf9 as an immediate early gene reduces cell proliferation with the induction of $p21^{cip1}$ and the enhancement of c-Jun degradation (Narla et al., 2001; Slavin et al., 2004), thus functioning as a potential tumor suppressor gene. Activation of Zf9 includes its phosphorylation at serine (or tyrosine) residues (Warke et al., 2003). Thus, phosphorylation of Zf9 leads to transcription of its target genes (Warke et al., 2003; Slavin et al., 2004). However, the kinase catalyzing Zf9 phosphorylation has not been studied yet.

In the present study, we attempted to determine whether PPARγ-RXR heterodimer represses the *TGFβ1* gene, and if so, what signaling pathway regulates the gene repression and phosphorylation of Zf9. In addition, we tried to determine whether the nuclear receptor heterodimer activates the putative PPREs located in the promoter region of the *TGFβ1* gene. We found that activation of PPARγ and RXR heterodimer results in the inhibition of S6K1 activity, which contributes to *TGFβ1* gene repression. Because phosphatase and tensin homolog deleted on chromosome 10 (PTEN) antagonizes the PI3-kinase-mTOR-S6K1-mediated signaling cascade (Liu et al., 2005), we also explored the effect of PGJ_2 + RA on the expression of PTEN and the role of PTEN up-regulation in the S6K1 inhibition for *TGFβ1* gene repression by PGJ_2 + RA.

Materials and Methods

Materials. PGJ_2 were purchased from BIOMOL Research Laboratories (Plymouth Meeting, PA). Pioglitazone and rosiglitazone were supplied from Dong-A Pharmaceutical Co. (Shingal, Korea). RA, rapamycin, and anti-phosphoserine antibody were purchased from Sigma-Aldrich (St. Louis, MO). Anti-NF1 antibody, anti-SP1 antibody, and anti-Zf9 antibody were obtained from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA). The antibodies directed against S6 protein, phosphorylated S6 protein, and PTEN were supplied from Cell Signaling Technology Inc. (Beverly, MA). Horseradish peroxidase-conjugated goat anti-rabbit and rabbit anti-goat IgGs were purchased from Zymed Laboratories (South San Francisco, CA). A series of deletion constructs of pGL3-TGFβ1 containing the human *TGFβ1* promoter region were kindly provided from Dr. S. J. Kim (National Cancer Institute, Bethesda, MD). The expression construct encoding mouse PPARγ1 (pCMX-mPPARγ1) was supplied from Dr. C. K. Glass (University of California, San Diego, CA). The human RXRα expression plasmid (PECE-RXRα) was a gift from Dr. M. O. Lee (Seoul National University, Seoul, Korea). The S6K1 expression constructs PRK5 myc-tagged 2BQ (dominant negative, DN-S6K1) and D3E (constitutively active, CA-S6K1) were supplied from Dr. J. H. Han (Sungkyunkwan University, Suwon, Korea), originally provided by Dr. G. Thomas (Friedrich Miescher Institut, Basel, Switzerland) (Hannan et al., 2003; Pesce et al., 2003). The PTEN expression plasmid was donated by Dr. S. G. Rhee (National Institutes of Health, Bethesda, MD).

Cell Culture. L929, a mouse fibroblast cell line was obtained from American Type Culture Collection (Manassas, VA). Cells were maintained in Dulbecco's modified Eagle's medium containing 10% fetal bovine serum (FBS), 50 U/ml penicillin, and 50 μg/ml streptomycin at 37°C in a humidified atmosphere with 5% CO_2. L929 cells that had been cultured in the medium containing 10% FBS were incubated without serum for 12 h and then exposed to PGJ_2, RA, PGJ_2 + RA, pioglitazone, or rosiglitazone, dissolved in dimethyl sulfoxide, for the indicated time period at 37°C.

Reverse Transcription-Polymerase Chain Reaction and Real-Time Reverse Transcription-Polymerase Chain Reaction. Total RNA was isolated from L929 cells using the improved single-step method of thiocyanate-phenol-chloroform RNA extraction, and RT-PCR analysis was carried out according to the procedures described previously (Kang et al., 2002). In this study, we used semiquantitative RT-PCR analysis, which was proven to be adequate for quantification of TGFβ1 mRNA levels (Kruse et al., 1999). RT-PCR was performed using the selective primers for TGFβ1 (sense primer, 5′-CTTCAGCTCCACAG AGAAGAACTGC-3′ and antisense primer, 5′-CACGATCATGTTGGACAACTGCTCC-3′; 298 bp) and glyceraldehyde-3-phosphate dehydrogenase (GAPDH) genes (sense, 5′-TCGTGGAGTCTACTGGCG T-3′ and antisense, 5′-GCCTGCTTCACCACCTTCT-3′; 510 bp). PCRs were carried out for 26 to 29 cycles using the following conditions: denaturation at 94°C for 0.5 min, annealing at 54°C for 0.5 min, and elongation at 72°C for 1 min, and the optimal cycle was selected for quantification. Band intensities of the amplified DNAs were compared after visualization on an UV transilluminator (Alpha-Innotech, San Leandro, CA). In some

experiments, real-time PCRs were performed in a Light Cycler 1.5 (Roche Diagnostics, Mannheim, Germany) using Light Cycler DNA Master SYBR Green I kit according to the manufacturer's instruction. A thermal profile for SYBR Green RT-PCR was 95°C for 10 min, followed by 40 cycles at 95°C for 10 s, at 51°C for 5 s, and at 72°C for 15 s. A melting curve analysis was done after amplification to verify the accuracy of the amplicon.

Luciferase Reporter Gene Analysis. To determine TGFβ1 activity, we used the dual-luciferase reporter assay system (Promega, Madison, WI). In brief, L929 cells (7×10^5 cells/well) were replated in six-well plates overnight, serum-starved for 12 h, and transiently transfected with pGL3-TGFβ1 promoter-luciferase construct and 0.3 μg of pCMV-β-galactosidase plasmid (Invitrogen, Carlsbad, CA) in the presence of LipofectAMINE reagent (Invitrogen) for 3 h. The pCMV-β-galactosidase plasmid was used to evaluate the transfection efficiency. Transfected cells were incubated in the medium containing 1% FBS (Invitrogen) for 3 h and exposed to PGJ_2 + RA (30 nM each) in the medium containing 1% FBS for 12 h at 37°C. For β-galactosidase activity, 10 μg of cell lysates was added to the solution containing 0.88 mg/ml *o*-nitrophenyl-β-D-galactopyranoside, 100 μM $MgCl_2$, and 47 mM β-mercaptoethanol in 100 mM sodium phosphate buffer. The reaction mixture was incubated for 2 h at 37°C, and the absorbance was determined at 420 nm. The relative luciferase activity was calculated by normalizing firefly luciferase activity to that of β-galactosidase. In case of PPARγ and/or RXRα overexpression, cells were cotransfected with pCMX-mPPARγ1 and/or PECE-RXRα in combination with pGL3-323 and incubated in the medium containing 1% FBS for 12 h. In some experiments, cells were transfected with the plasmid encoding CA-S6K1 or DN-S6K1 in combination with pGL3-323 and incubated in the medium containing PGJ_2 + RA for 12 h.

Preparation of Cell Lysates and Nuclear Extracts. Lysates and nuclear extracts were prepared according to previously published methods (Park et al., 2004). In brief, cells were centrifuged at 2300*g* for 3 min and allowed to swell after the addition of the lysis buffer. The samples were centrifuged at 10,000*g* for 10 min to obtain cell lysates. To prepare nuclear extracts, cells were allowed to swell after the addition of 100 μl of hypotonic buffer. The lysates were incubated for 10 min on ice and then centrifuged at 7200*g* for 5 min at 4°C. Pellets containing crude nuclei were resuspended in 50 μl of extraction buffer. Nuclear extracts were prepared from the samples by centrifugation at 15,000*g* for 10 min and stored −70°C until use. Protein content was determined by the Bradford assay (Bio-Rad protein assay kit; Bio-Rad, Hercules, CA).

S6K1-Immune Complex Kinase Assay. To determine the S6K1 activity, S6K1 in cell lysates (200 μg) was immunoprecipitated, and the samples were washed three times in lysis buffer and once in the kinase buffer containing 25 mM Tris-HCl, pH 7.4, 10 mM $MgCl_2$, 25 mM β-glycerophosphate, 1 mM Na_3VO_4, 2 mM dithiothreitol, 1 mM phenylmethylsulfonyl fluoride, 1 μg/ml leupeptin, and 200 μM ATP. Kinase reaction was initiated by adding S6 substrate peptide (5 μg per assay) and 2 μCi of [γ-^{32}P]ATP to a 20-μl reaction mixture and continued for 30 min at 30°C. After brief centrifugation, the supernatant of reaction mixture was spotted onto p81 phosphocellulose paper (Upstate, Lake Placid, NY). The paper was washed with 0.8% phosphoric acid for 5 min three times and subsequently with 90% ethanol for 5 min. The membrane was dried and transferred to 5 ml of scintillation cocktail, and the radioactivity of phosphorylated substrate was measured using a beta-counter (PerkinElmer Wallac, Gaithersburg, MD).

Immunoprecipitation. To determine serine phosphorylations of Zf9, NF1, or SP1, fractions of lysates or nuclear extracts were incubated with the respective antibodies overnight at 4°C for immunoprecipitation. Immune complex precipitated with protein G-agarose was solubilized in 2× Laemmli buffer and boiled. Samples were resolved in 7.5% SDS-polyacrylamide gel electrophoresis and then transferred to nitrocellulose membranes. The samples were immunoblotted with anti-phosphoserine antibody. The bands were developed using an ECL chemiluminescence detection kit (GE Healthcare, Little Chalfont, Buckinghamshire, UK).

Transient Transfection. Cells (5×10^5 cells/well) were replated in six-well plates overnight, serum-starved for 6 h, and transiently transfected with pCMX-mPPARγ1 and/or PECE-RXRα (0.5 μg each) in the presence of LipofectAMINE reagent. The transfected cells were incubated in the medium containing 1% FBS for 3 h and subjected to immunoblot analysis. Cells were also transfected with the plasmid encoding PTEN (0.3 or 1 μg) with or without empty plasmid to adjust the total amount of plasmids transfected to 1 μg.

Immunoblot Analysis. SDS-polyacrylamide gel electrophoresis and immunoblot analysis were performed according to previously published procedures (Park et al., 2004) with antibodies specifically directed against Zf9, NF1, SP1, S6 protein, actin, or PTEN.

Statistical Analysis. Scanning densitometry was performed with Image Scan and Analysis System (Alpha-Innotech). One-way analysis of variance procedures were used to assess significant differences among treatment groups. For each significant effect of treatment, the Newman-Keuls test was used for comparisons of multiple group means. The criterion for statistical significance was set at $p < 0.05$ or $p < 0.01$. All statistical tests were two-sided.

Results

Repression of the *TGFβ1* Gene by PGJ_2 + RA. To examine the role of PPARγ activation in TGFβ1 expression, we first assessed the dose-dependent effects of PGJ_2, an endogenous PPARγ agonist, or RA, a RXR agonist, on TGFβ1 expression in L929 cells (Fig. 1A). Semiquantitative RT-PCR analysis showed that PGJ_2, at the concentration of 100 or 1000 nM inhibited TGFβ1 expression 20 to 40% 12 h after treatment, indicating that PGJ_2 at the relatively high concentrations weakly inhibited the gene expression. Treatment of the cells with 30 to 100 nM RA for 12 h also repressed the level of TGFβ1 mRNA by 30 to 40% (Fig. 1A). RA at 1000 nM blocked TGFβ1 expression by >50%. Data showed that either PGJ_2 or RA alone moderately decreased the expression of *TGFβ1* gene in L929 fibroblasts.

PPARγ heterodimerizes with RXR for activation, and the PPARγ-RXR heterodimers are widely expressed in major organs (Dubuquoy et al., 2002). Next, we determined whether PGJ_2 + RA inhibited TGFβ1 expression. In our previous study, PGJ_2 + RA enhanced class α glutathione *S*-transferase gene expression to the greatest extent at the 1:1 molar ratio (Park et al., 2004). Therefore, in the subsequent experiments, the cells were similarly treated with PGJ_2 + RA. Compared with the individual treatment, combination treatment of PGJ_2 and RA at equal molar concentrations synergistically down-regulated TGFβ1. TGFβ1 expression was inhibited 40% by treatment of the cells with PGJ_2 + RA as low as at 10 nM each (Fig. 1B). PGJ_2 + RA at the concentrations of 30 to 100 nM inhibited TGFβ1 expression 70 to 80%. A time-course study using 30 nM each of PGJ_2 and RA showed that the TGFβ1 mRNA levels were markedly decreased 12 to 24 h after treatment (Fig. 1C). Real-time RT-PCR analysis using SYBR Green I confirmed the synergistic repression of *TGFβ1* gene expression by PGJ_2 + RA treatment compared with PGJ_2 or RA treatment alone (Fig. 1D), implying that PPARγ activation in combination with that of RXR efficaciously down-regulates the *TGFβ1* gene.

PPARγ-Dependent Repression of *TGFβ1* Gene by PGJ_2 + RA. The role of PPARγ activation in TGFβ1 repression was examined by the experiments using thiazolidinedi-

one PPARγ agonists. Treatment of L929 cells with either 10 μM rosiglitazone or 10 μM pioglitazone for 12 h significantly decreased the expression of TGFβ1 mRNA (Fig. 2A). The suppressed TGFβ1 transcript by rosiglitazone or pioglitazone confirms the role of ligand activation of PPARγ in TGFβ1 repression.

To further verify the role of PPARγ in the regulation of *TGFβ1* gene, we examined the effects of PPARγ antagonists on the *TGFβ1* expression and on the repression of *TGFβ1* by PGJ_2 + RA. Treatment of L929 cells with a PPARγ antagonist BADGE (10 μM; 13 h) alone significantly increased the gene expression and abrogated TGFβ1 repression elicited by PGJ_2 + RA (30 nM each) (Fig. 2B, left). Increase in TGFβ1 expression by BADGE treatment suggests that activated PPARγ serves as an endogenous negative regulator for TGFβ1 expression. Another PPARγ antagonist, GW9662 (1 μM), also completely blocked TGFβ1 repression by PGJ_2 + RA (Fig. 2B, right). These data showed that activation of PPARγ, which in combination with RXR activation enhances TGFβ1 repression, plays a critical role in the regulation of the *TGFβ1* gene.

TGFβ1 Reporter Gene Analysis with Promoter Deletions. The effects of PPARγ and RXR activation on the *TGFβ1* gene transactivation that is regulated by the proximal DNA response elements were examined as an effort to identify the molecular basis of TGFβ1 repression by PGJ_2 + RA. The potential regulatory sites responsible for the *TGFβ1* gene expression were first explored by using the luciferase reporter gene assays. To precisely define the role of DNA elements interacted with transcription factors in the gene repression, this study used a series of promoter deletion mutants: the deletion mutants of the structural *TGFβ1* gene downstream of the −1.36-kilobase promoter region included pGL3-1362, pGL3-1132, pGL3-731, pGL3-453, pGL3-323, and pGL3-175 (Fig. 3A). The putative PPREs were located at the multiple sites upstream from −453 bp of the promoter region.

Exposure of pGL3-1132-transfected cells to PGJ_2 + RA (30 nM each) resulted in a 35% decrease in the luciferase activity (Fig. 3B). PGJ_2 + RA decreased the relative luciferase-inducible activity by 50% in cells transfected with pGL3-731, compared with vehicle-treated control. TGFβ1 repression by PGJ_2 + RA was unaffected by deletion of the promoter containing the region down to −453 bp. Luciferase activity was down-regulated by PGJ_2 + RA treatment in cells transfected with pGL3-453 that contains no putative PPREs, indicating that the putative PPRE sites located at the upstream region were not functional for the gene repression. We further examined whether PGJ_2 + RA had the ability to repress reporter gene expression from pGL3-323 that misses the AP-1 binding sites present within the region between −453 and −323 bp. Although the constitutive luciferase expression was largely decreased by deletion of the AP-1-containing region, PGJ_2 + RA still inhibited luciferase expression from pGL3-323. Such promoter deletion analyses indicate that PGJ_2 + RA significantly inhibits luciferase reporter activity in cells transfected with the *TGFβ1* promoter, suggesting that neither the putative PPREs nor the AP-1 binding sites are directly regulated by PGJ_2 + RA for the gene repression.

Inhibition of S6K1 by PGJ_2 + RA. Because S6K1 has been implicated in the regulation of fibrogenesis (Zhu et al., 1999), we sought to determine the effects of PGJ_2 + RA on the activity of S6K1 in association with *TGFβ1* gene repression. The S6K1 is a physiological kinase that phosphorylates 40S ribosomal S6 protein in cells (Chung et al., 1992). PGJ_2 + RA decreased phosphorylation of S6 protein 3 to 12 h after

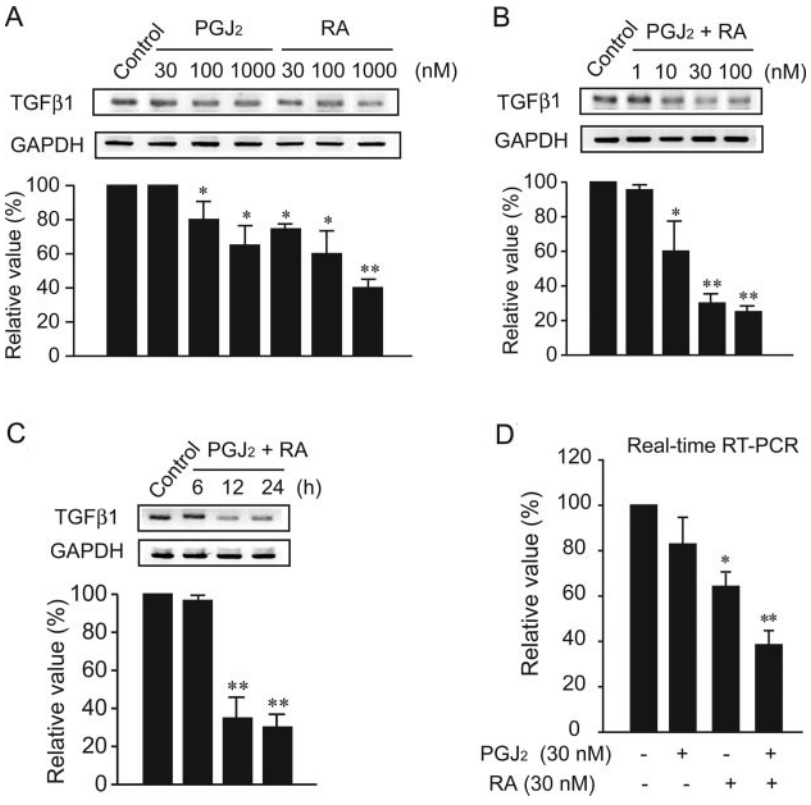

Fig. 1. Effects of PGJ_2 and/or RA on *TGFβ1* gene expression. A, RT-PCR analysis of the TGFβ1 mRNA levels. Semiquantitative RT-PCR analyses were performed in the total RNA prepared from L929 cells treated with 30 to 1000 nM PGJ_2 or RA for 12 h. The GAPDH mRNA levels were monitored as controls. The change in TGFβ1 mRNA relative to that of GAPDH was assessed by scanning densitometry of the band intensities. B, effect of PGJ_2 + RA on TGFβ1 mRNA expression. Representative RT-PCR analysis shows the levels of TGFβ1 mRNA in cells treated with PGJ_2 + RA at the concentrations of 1 to 100 nM each for 12 h. C, the relative TGFβ1 mRNA levels in cells treated with PGJ_2 + RA (30 nM each) for 6 to 24 h. D, real-time RT-PCR analysis. Real-time RT-PCR analysis was performed in the total RNA prepared from cells treated with PGJ_2 or RA alone or in combination for 12 h. Data represent the mean ± S.D. with three separate experiments (significant compared with control: $*, p < 0.05$, $**, p < 0.01$) (TGFβ1 mRNA level in control, 100%).

treatment (Fig. 4A, left). The inhibition of S6 protein phosphorylation sustained at least up to 24 h (data not shown). A concentration-response study indicated that S6 protein phosphorylation was decreased by PGJ_2 + RA at the concentrations of 10 nM each or above (Fig. 4A, right). Furthermore, we measured the kinase activity of S6K1 immunoprecipitated in the lysates of cells treated PGJ_2 + RA. PGJ_2 + RA treatment consistently decreased the immune complex kinase activity in a time- and concentration-dependent manner (Fig. 4B).

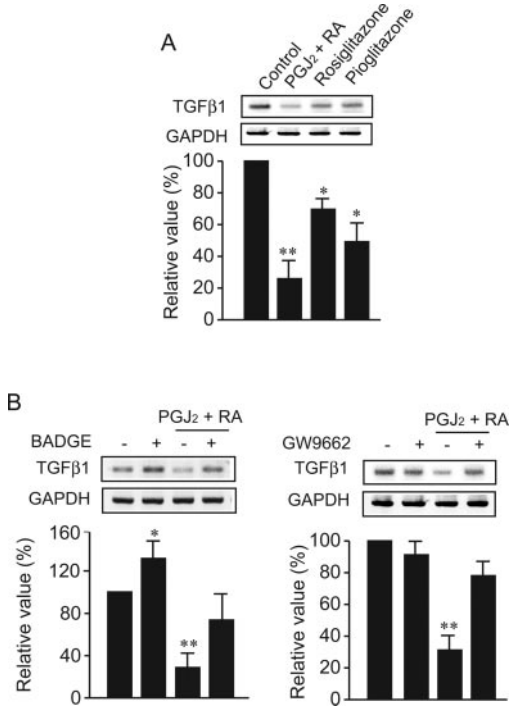

Fig. 2. PPARγ-dependent repression of the *TGFβ1* gene by PGJ_2 + RA. A, repression of the TGFβ1 mRNA expression by thiazolidinediones. TGFβ1 expression was measured in L929 cells treated with 10 μM rosiglitazone or pioglitazone for 12 h. B, effect of the PPARγ antagonists on TGFβ1 repression by PGJ_2 + RA. Cells were pretreated with 10 μM BADGE or 1 μM GW9662 for 1 h and subsequently exposed to PGJ_2 + RA (30 nM each) for 12 h in the continuing presence of BADGE or GW9662. Data represent the mean ± S.D. with three separate experiments (significant compared with control: *, $p < 0.05$, **, $p < 0.01$) (TGFβ1 mRNA level in control, 100%).

Role of S6K1 Inhibition by PGJ_2 + RA in Zf9 Dephosphorylation. The transcription factors that interact with the known DNA binding sites on the region downstream within the −323 bp of the *TGFβ1* gene include Zf9, NF1, and SP1 (Fig. 3A). In view of the previous observations that Zf9 is crucial as a transcription factor for TGFβ1 induction in hepatic stellate cells (Kim et al., 1998) and that phosphorylated form of Zf9 plays a role in the transactivation of the target gene promoter (Warke et al., 2003), we next investigated the potential ability of PGJ_2 + RA to inhibit serine phosphorylation of the transcription factor. Immunoblotting for phosphorylated serine in Zf9 immunoprecipitates from lysates revealed that serine phosphorylation of Zf9 was markedly inhibited by PGJ_2 + RA treatment (6 h) (Fig. 5A). In contrast, NF1 and SP1 phosphorylations were unaffected. Therefore, it was presumed that *TGFβ1* gene repression by PGJ_2 + RA might have resulted from dephosphorylation of Zf9.

Given the inhibition of S6K1 activity by PGJ_2 + RA, we next determined the effect of S6K1 inhibition on Zf9 dephosphorylation. The inhibition of Zf9 phosphorylation by rapamycin that inhibits S6K1 activity via mTOR inhibition supported the role of S6K1 in Zf9 phosphorylation (Fig. 5B). As expected, serine-phosphorylated Zf9 level was also decreased by PGJ_2 + RA treatment (6 h). Inhibition of S6 protein phosphorylation by the agents was confirmed (Fig. 5B). To verify the role of S6K1 activity in Zf9 phosphorylation, we tested whether PGJ_2 + RA inhibition of Zf9 phosphorylation was reversed by the constitutive activation of S6K1. Multiple analyses showed that Zf9 phosphorylation in untreated cells that express CA-S6K1 was comparable with that in mock-transfected cells, which may have resulted from saturation of Zf9 phosphorylation in L929 cells because of its high constitutive phosphorylation and/or the limit of detection method

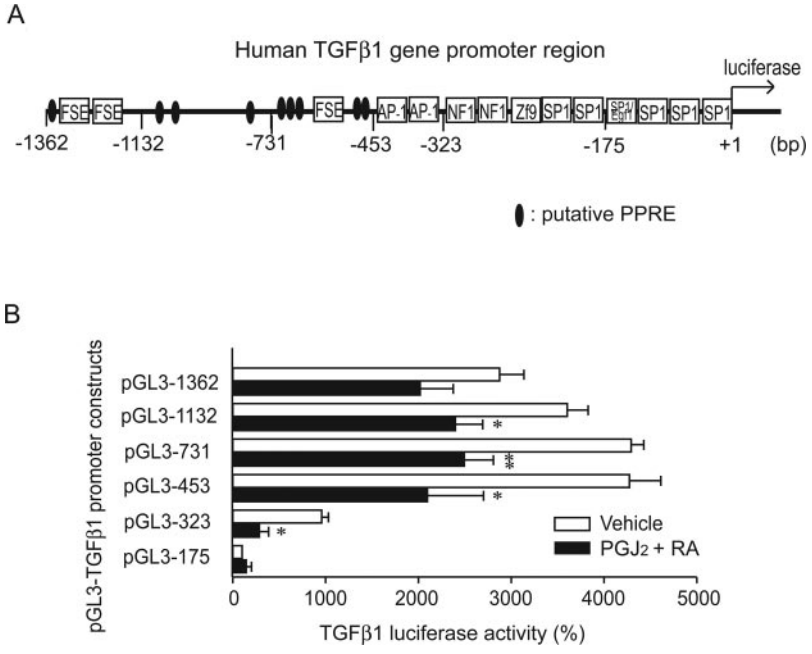

Fig. 3. Promoter deletion analysis of the *TGFβ1* gene. A, promoter region of the *TGFβ1* gene construct. The promoter region of *TGFβ1* gene containing up to −1362 bp shows the fat-specific element (FSE), putative PPREs, AP-1, NF1, Zf9, and SP1 DNA binding elements at multiple locations. B, repression of luciferase activity by PGJ_2 + RA. Luciferase reporter assays were performed in the lysates of L929 cells transfected with the TGFβ1 luciferase reporter construct and subsequently exposed to PGJ_2 + RA (30 nM each) for 12 h. Data represented the mean ± S.D. with three separate experiments (significant compared with vehicle for the respective construct transfection: *, $p < 0.05$, **, $p < 0.01$) (luciferase activity in pGL3-175-transfected cells treated with vehicle, 100%).

(i.e., Zf9 immunoprecipitation and pan-phosphoserine antibody immunoblot). More importantly, transfection of the cells with CA-S6K1 abrogated dephosphorylation of Zf9 elicited by PGJ_2 + RA (Fig. 5C). We verified good transfection efficiency of CA-S6K1 in the cells by immunocomplex kinase assay of S6K1 (2.3-fold increase relative to mock transfection). Our finding that Zf9 dephosphorylation was antagonized by CA-S6K1 supports the possibility that PGJ_2 + RA inhibits *TGFβ1* gene transcription via Zf9 dephosphorylation because of S6K1 inhibition.

Role of S6K1 in *TGFβ1* Gene Expression. Next, to assess the role of S6K1 for the *TGFβ1* gene expression, pGL3-323 luciferase assay was performed in cells treated with PGJ_2 + RA after transfection with the plasmid encoding CA-S6K1. CA-S6K1 transfection abrogated the ability of PGJ_2 + RA to repress luciferase expression from pGL3-323 (Fig. 6, left). It seems that the basal *TGFβ1* reporter gene activity was rather increased by CA-S6K1 transfection alone. As expected, DN-S6K1 transfection inhibited luciferase expression from pGL3-323 (Fig. 6, right). Data presented here identifies the role of S6K1 inhibition by PGJ_2 + RA for *TGFβ1* gene repression.

TGFβ1 Repression by PPARγ1-RXRα-Mediated S6K1 Inhibition. To further verify the functional role of the PPARγ-RXRα heterodimer in the inhibition of the *TGFβ1* gene, we monitored luciferase expression from pGL3-323 in cells transfected with PPARγ1 or/and RXRα. Either PPARγ1 or RXRα alone significantly inhibited pGL3-323 gene expression (Fig. 7A). Furthermore, transfection of cells with both PPARγ1 and RXRα almost abolished luciferase expression from pGL3-323, the extent of which was comparable with that elicited by PGJ_2 + RA. Results from this receptor overexpression experiment demonstrate that activation of PPARγ-RXR heterodimer indeed contributes to the *TGFβ1* gene repression. Furthermore, we determined whether PPARγ-RXRα overexpression led to inhibition of S6 protein phosphorylation. Either PPARγ or RXRα alone, or in combination, notably inhibited the phosphorylation of S6 protein

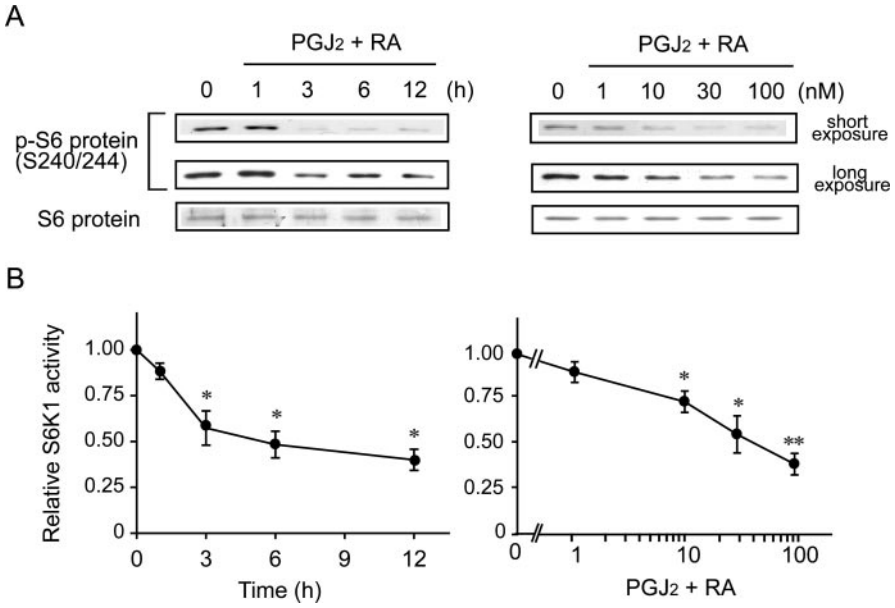

Fig. 4. S6K1 inhibition by PGJ_2 + RA. A, effect of PGJ_2 + RA on the phosphorylation of S6 protein. S6 protein phosphorylation was determined in the lysates prepared from cells treated with PGJ_2 + RA (30 nM each) for 1 to 12 h or those treated with 1 to 100 nM PGJ_2 + RA for 6 h. B, effect of PGJ_2 + RA on S6K1 immune complex kinase activity. The kinase activity of S6K1 toward S6 substrate peptide was determined by monitoring ^{32}P radioactivity in the S6K1 immune complex precipitated from lysates. Data represent the mean ± S.D. with three separate experiments (significant compared with control: *, $p < 0.05$, **, $p < 0.01$) (S6K1 activity in control, 1).

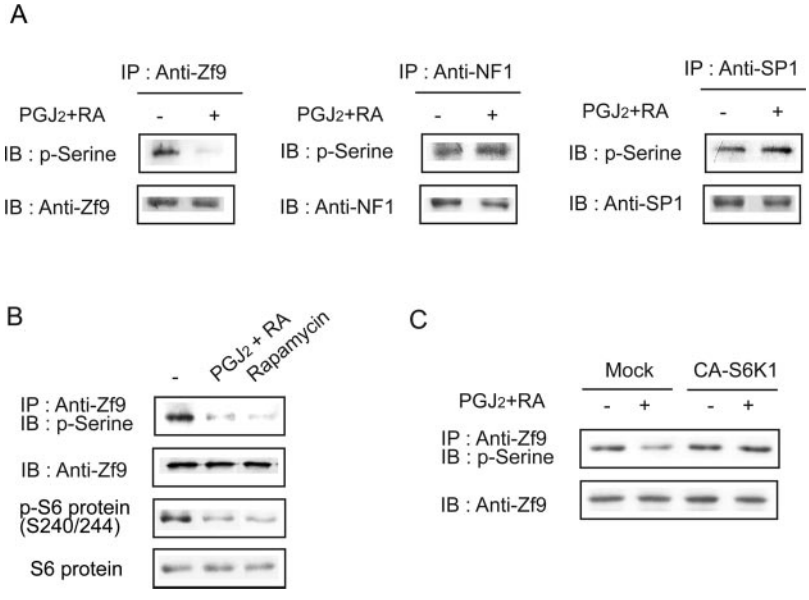

Fig. 5. Role of S6K1 inhibition by PGJ_2 + RA in Zf9 dephosphorylation. A, inhibition of Zf9 dephosphorylation by PGJ_2 + RA. Immunoblot analyses were performed with anti-phosphoserine antibody in Zf9, NF1, or SP1 immunoprecipitates obtained from the lysates (200 μg each) of cells treated with vehicle or PGJ_2 + RA for 6 h. B, Zf9 dephosphorylation by PGJ_2 + RA or rapamycin. Immunoblot analysis for serine-phosphorylated Zf9 was carried out in the nuclear fractions of cells treated with PGJ_2 + RA (30 nM each) or rapamycin (30 nM) for 6 h. C, CA-S6K1 reversal of Zf9 dephosphorylation by PGJ_2 + RA. Cells were transfected with the empty plasmid (mock) or the plasmid encoding CA-S6K1 (0.5 μg each), incubated in the medium containing 1% FBS for 12 h, and then treated with PGJ_2 + RA for 6 h. Immunoblottings for phosphorylated serine were carried out in Zf9 immunoprecipitates from the nuclear extracts. S6K1 immune complex kinase activity in cells transfected with CA-S6K1 construct was 2.3-fold increased compared with that in mock-transfected cells. Results were confirmed by three independent experiments.

(Fig. 7B). As anticipated, pGL3-323 *TGFβ1* gene repression by PPARγ and RXRα was reversed by transfection with CA-S6K1 (Fig. 7C). Again, CA-S6K1 transfection alone increased the basal gene expression. These results provide evidence that the activation of PPARγ-RXRα results in the inhibition of S6K1 and that the S6K1 inhibition was responsible for the *TGFβ1* gene repression.

Role of PGJ_2 + RA-Mediated PTEN Induction for S6K1 Inhibition. Functional PPREs are located in the PTEN promoter (Patel et al., 2001). It has been shown that PPARγ activation induces PTEN, which antagonizes PI3-kinase-mediated cell signaling (Lee et al., 2005). To study more in depth the mechanistic basis of the inhibition of *TGFβ1* gene by PGJ_2 + RA, we determined whether ligand activation of PPARγ-RXRα was capable of inducing PTEN. A time-course study revealed that PGJ_2 + RA treatment induced PTEN in L929 fibroblast cells, beginning from 3 h at least up to 12 h after treatment (Fig. 8A). We further examined the effect of ectopic PTEN expression on the phosphorylation of S6 protein and *TGFβ1* gene expression. S6 protein phosphorylation notably decreased after PTEN induction presumably through decrease in the formation of phosphatidylinositol-(3,4,5)-trisphosphate, whose production is catalyzed by PI3-kinase (Fig. 8B). *TGFβ1* gene was also repressed by PTEN expression (Fig. 8C). To verify the antagonism of PI3-kinase activity against TGFβ1 repression by PGJ_2 + RA, PGJ_2 + RA-dependent luciferase gene expression was measured in cells transfected with the plasmid encoding p110, the catalytic subunit of PI3-kinase. The basal *TGFβ1* reporter gene activity from pGL3-323 was increased by p110 transfection (Fig. 8D). More importantly, p110 overexpression inhibited the ability of PGJ_2 + RA to repress luciferase expression from pGL3-323. Together, these data indicate that the induction of PTEN by PGJ_2 + RA may result in *TGFβ1* gene repression as a consequence of S6K1 inhibition.

Effects on Cellular Kinases Downstream of PTEN. Finally, we observed that PGJ_2 + RA treatment inhibited phosphorylations of the major cellular kinases (Akt, ERK1/2, RSK1, and mTOR) downstream of PTEN (Fig. 9A). The results indicate that PTEN induction by PGJ_2 + RA leads to S6K1 inhibition via the pathways of ERK1/2-RSK1 as well as Akt-mTOR (Fig. 9B).

Discussion

Studies on the regulation of the *TGFβ1* gene and the molecular interactions of ligand-activated nuclear receptors for the activation of responsible transcription factor(s) provide insight into the transcriptional control mechanism. In the

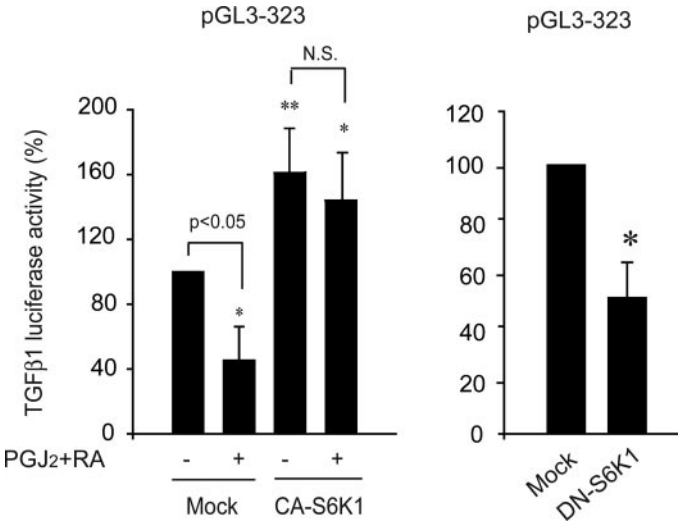

Fig. 6. Role of S6K1 inhibition in TGFβ1 repression by PGJ_2 + RA. Cells were transfected with pGL3-323 in combination with the empty plasmid (mock) or the plasmid encoding CA-S6K1 (0.5 μg) for 3 h and further incubated in the medium containing 1% FBS for 16 h. Luciferase activity was determined in the lysates prepared from cells treated with PGJ_2 + RA for 12 h. Luciferase activity from pGL3-323 was also assayed in cells transfected with DN-S6K1 (0.5 μg). Data represented the mean ± S.D. with three separate experiments (significant compared with mock-transfected control: *, $p < 0.05$, **, $p < 0.01$) (luciferase activity in vehicle-treated mock-transfected cells, 100%).

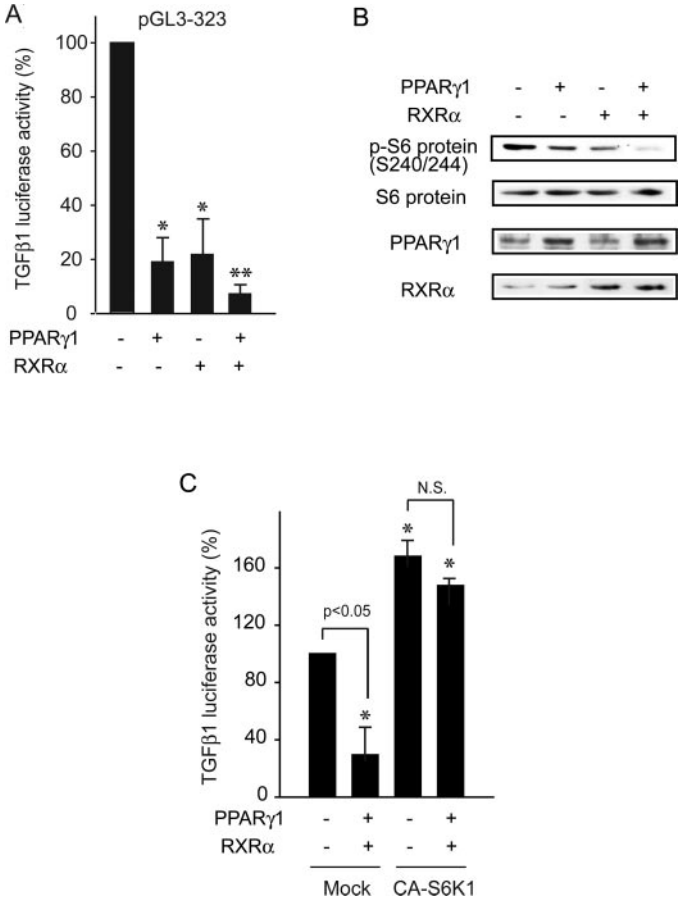

Fig. 7. Role of S6K1 inhibition in TGFβ1 repression by PPARγ1-RXRα heterodimer. A, *TGFβ1* gene repression by PPARγ1 and RXRα heterodimer. Cells were transfected with pGL3-323 (1 μg) in combination with an empty vector or with the PPARγ1 or/and RXRα plasmids (0.5 μg each) in the presence of LipofectAMINE for 3 h and incubated in the medium containing 1% FBS for 12 h. Luciferase activity from pGL3-323 was measured in cell lysates. B, inhibition of S6 protein phosphorylation by PPARγ1-RXRα heterodimer. Serine-phosphorylated S6 protein was determined by immunoblotting in the lysates of cells transfected with the PPARγ1 or/and RXRα plasmids, as described in A. C, TGFβ1 luciferase activity. Luciferase activity from pGL3-323 was determined in the lysates prepared of cells transfected with the PPARγ1 and RXRα plasmids (0.5 μg each) with or without an empty plasmid (mock) or the plasmid encoding CA-S6K1 (0.5 μg). The total amount of plasmids transfected was identical in each sample (1.5 μg). Data represented the mean ± S.D. with three separate experiments (significant compared with mock-transfected control: *, $p < 0.05$, **, $p < 0.01$) (luciferase activity in mock transfection, 100%).

present study, we demonstrated that either PPARγ or RXR agonist alone at relatively high concentrations down-regulated the *TGFβ1* gene, whereas concomitant treatment with both PPARγ and RXR agonists synergistically repressed the gene. PGJ_2 at low concentrations serves as an agonist of PPARγ. RXRs are modular proteins with a highly conserved central DNA binding domain and a less conserved ligand binding domain (Holmbeck et al., 1998). PGJ_2 alone at low nanomolar concentrations is a weak repressor of TGFβ1 because activated PPARγ requires additional binding of ligand-bound RXR for the formation of a PPARγ-RXR heterodimer. This is consistent with the current observation that RA potentiated *TGFβ1* gene repression by PGJ_2, although RA alone weakly repressed the gene. Enhanced TGFβ1 repression by PGJ_2 + RA, compared with that by each agent alone, implies that PPARγ and RXR heterodimer activation contributes to the gene regulation. Our hypothesis was strongly supported by the observation that ectopic expression of PPARγ1 and RXRα almost completely inhibited luciferase expression from pGL3-323. The role of PPARγ in the repression of the *TGFβ1* gene was further evidenced by the repressing effect of its glitazone ligand and also by the reversal of *TGFβ1* repression by PPARγ antagonists. Our results presented here identify the novel aspect that PPARγ activation contributes to *TGFβ1* gene down-regulation and that ligand activation of RXRα is necessary for the full responsiveness in the gene repression by PPARγ activator.

Such a finding showing PGJ_2 + RA-mediated *TGFβ1* gene repression with deletion of the promoter region comprising the putative PPREs lends support to the conclusion that the putative binding sites for PPARγ-RXR in the promoter region are neither active nor responsible for the gene repression by activated PPARγ and RXR heterodimer. The promoter region of human *TGFβ1* gene contains two AP-1 binding sites that mediate up-regulation of the gene in response to the conditions of mitogen-activated protein kinase activation such as phorbol esters or hyperglycemia (Kim et al., 1989b; Weigert et al., 2000). The studies showed that the AP-1 binding sites, located at between −453 and −323 bp, play a crucial role in TGFβ1 up-regulation. The cell signaling pathways involving protein kinase C and p38 kinase enhance AP-1 binding to its DNA binding elements predominantly to the proximal AP-1 box in the TGFβ1 promoter (Weigert et al., 2000). The proteins bound with the AP-1 binding elements in cells involve c-Jun, JunD, and c-Fos (Kim et al., 1990; Zhang et al., 1992; Lee et al., 2006). AP-1 interacts with CBP/p300 coactivator after complex formation with DNA, which is essential for AP-1-mediated gene transactivation (Kamei et al., 1996).

The effects of either PPARγ or retinoid ligands on *TGFβ1* gene expression have been claimed to be mediated in part by AP-1 inhibition (Salbert et al., 1993; Weigert et al., 2003). That deletion of the DNA region containing both AP-1 sites still had the capability to repress the gene by PGJ_2 + RA (Fig. 3) provides evidence that the AP-1 binding sites may not be a major regulatory target in the *TGFβ1* gene repression. In addition, we found that PGJ_2 + RA (30 nM each) did not alter the AP-1 promoter or DNA binding activity (Supplemental Data 1), suggesting that PPARγ-RXR activation does not affect AP-1. However, it should be noted here that specific mutation of the proximal AP-1 element (Weigert et al., 2000), primarily recognized by AP-1 complex, abolished the repressing effect of PGJ_2 + RA on *TGFβ1* promoter luciferase activity (Supplemental Data 2). This in conjunction with a substantial decrease in pGL-323 activity compared with AP-1

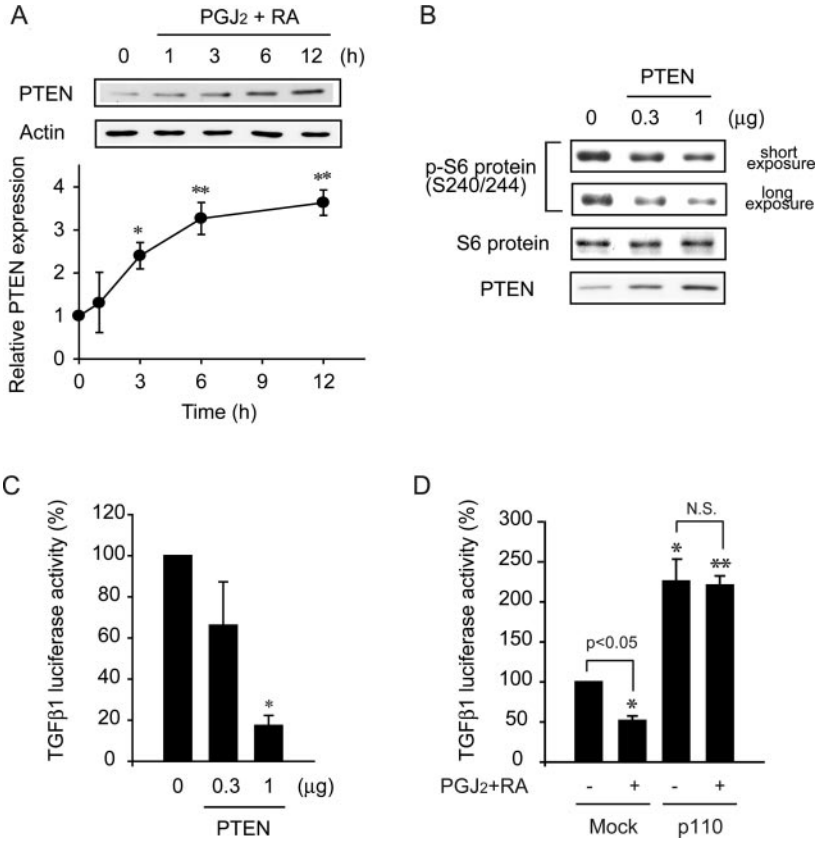

Fig. 8. Role of PTEN in TGFβ1 repression by PGJ_2 + RA. A, effect of PGJ_2 + RA on PTEN expression. PTEN was immunoblotted in the lysates of L929 cells treated with PGJ_2 + RA (30 nM each) for 1 to 12 h. B, effect of PTEN overexpression on S6 protein phosphorylation. Phosphorylated S6 protein was measured in cells transfected with a construct encoding PTEN. C, repression of TGFβ1 luciferase activity by PTEN overexpression. Cells were transfected with pGL3-323 in combination with an empty plasmid or the plasmid encoding PTEN. D, TGFβ1 luciferase activity. Luciferase activity from pGL3-323 was determined in the lysates prepared from cells treated with PGJ_2 + RA (30 nM each) for 12 h after transfection with an empty plasmid (mock) or the plasmid encoding p110 (0.5 μg). Data represented the mean ± S.D. with three separate experiments (significant compared with mock-transfected vehicle-treated control: *, $p < 0.05$, **, $p < 0.01$) (luciferase activity in vehicle-treated control, 100%).

box-containing pGL3-453 (Fig. 3) allows us to infer that the target molecule altered by PPARγ-RXRα-activated cell signal may be involved in the interaction with the protein recruited on the AP-1 DNA complex. Nonetheless, our observation that substantial repression of pGL3-323 lacking the AP-1 binding sites and putative PPREs by ectopic PPARγ and RXRα expression clearly indicates that the *TGFβ1* gene repression may have not resulted from direct inhibition of AP-1 but by other mechanistic bases.

S6K1, a ubiquitous serine/threonine kinase, controls the translational efficiency by phosphorylating ribosomal S6 protein (Jeno et al., 1988). Rapamycin inhibits S6K1 activity via mTOR inhibition. Yet, other pharmacological agents that modulate S6K1 activity, especially in association with Zf9 dephosphorylation, have not been reported. Our data presented here identify the efficacy of PGJ_2 + RA in suppressing S6K1 activity. The finding that S6K1 inhibition by PGJ_2 + RA was rapid and sustained suggests that the proposed signaling pathway may serve as a pharmacological molecular target. Our result showing that ectopic expression of PPARγ1 in combination with RXRα strongly inhibited S6K1 activity supports PPARγ-RXRα heterodimer as a target for S6K1 inhibition.

Zf9 as a transcription factor plays a crucial role for the induction of TGFβ1 (Kim et al., 1998). Studies have shown that Zf9 phosphorylation enhances its nuclear localization and transcriptional activity (Slavin et al., 2004). Thus, phosphorylation status of Zf9 contributes to the promotion of its target gene expression (Warke et al., 2003). In the present study, PGJ_2 + RA treatment repressed the luciferase activity of pGL3-323, whose promoter region comprises the DNA binding sites for Zf9, NF1, and SP1. Repression in TGFβ1 luciferase activity by PGJ_2 + RA paralleled decrease in the level of serine-phosphorylated Zf9. In contrast, PGJ_2 + RA treatment did not change phosphorylation of other transcription factors, NF1 and SP1. Thus, our studies here suggest that decrease in Zf9 phosphorylation contributes to the gene repression. Additional gel shift and chromatin immunoprecipitation experiments indicated that Zf9 (or phosphorylated Zf9) binding activity to its DNA binding site in the *TGFβ1* gene was unaffected (data not shown), implying that TGFβ1 repression by PGJ_2 + RA might result from a change in transactivating protein complex formation, such as recruitment of corepressor, presumably because of Zf9 dephosphorylation, but not a decrease in Zf9 DNA binding activity. As expected, we found that the NF1 and SP1 DNA binding activities were unchanged by PGJ_2 + RA treatment (data

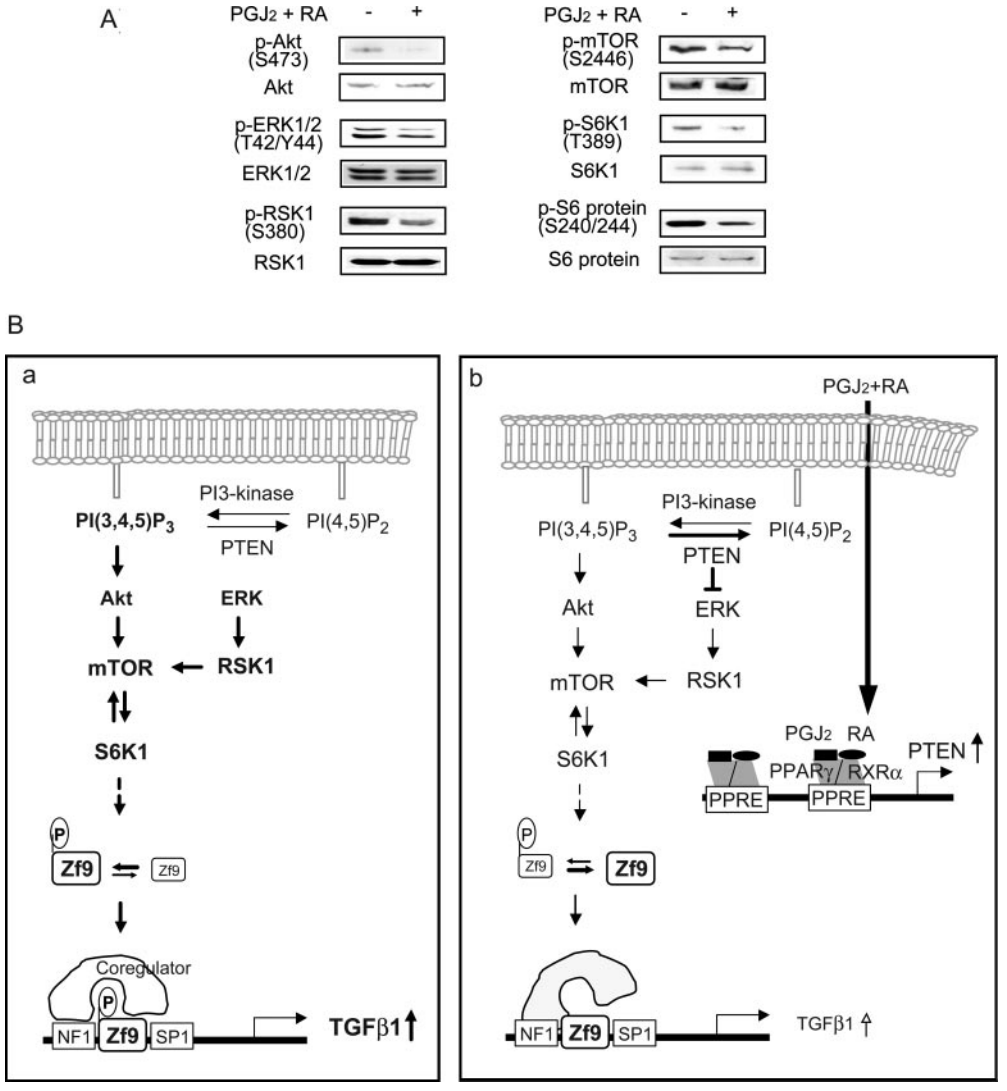

Fig. 9. Effects of PGJ_2 + RA treatment on the phosphorylations of cellular kinases downstream of PTEN. A, immunoblot analyses of Akt, ERK1/2, RSK1, mTOR, and S6K1 phosphorylated at regulatory sites. Phosphorylated forms of Akt (S473), ERK1/2 (T202/Y204), RSK1 (S380), mTOR (S2448), and S6K1 (T389) were immunoblotted by using their specific antibodies (Cell Signaling Technology Inc.) in the lysates (30 μg each for ERK1/2 or RSK1) or Akt, mTOR, or S6K1 immunoprecipitates prepared from lysates (200 μg each) of cells treated with vehicle or PGJ_2 + RA (30 nM each; 3 h). B, schematic diagram illustrating the proposed mechanism, by which activation of the PPARγ and RXR heterodimer represses the *TGFβ1* gene. a, basal untreated condition. b, effects of PGJ_2 + RA.

not shown). Identification of the partners of Zf9 or phosphorylated Zf9 for the gene regulation and their molecular interactions, which is beyond the scope of this study, constitutes an important question to answer.

The signaling pathway and the kinases responsible for Zf9 phosphorylation have not been elucidated. Either PMA/A23187 treatment or hypoxia, which has been implicated in the cell signaling pathway of S6K1, increased Zf9 phosphorylation (Warke et al., 2003; Skinner et al., 2004). An important finding of this study is that the pathway involving S6K1 mediates Zf9 phosphorylation. This was supported first by the observation that Zf9 phosphorylation was inhibited in cells treated with rapamycin, an mTOR and S6K1 inhibitor, and further strengthened by the finding that CA-S6K1 abolished Zf9 dephosphorylation by PGJ_2 + RA. Our results demonstrate that S6K1 (if not, another kinase downstream of S6K1) mediates Zf9 phosphorylation. The constitutive Zf9 phosphorylation by S6K1 highlights the important role of S6K1 as a multifunctional kinase for transcription factor regulation (de Groot et al., 1994; Harada et al., 2001; Wang et al., 2001).

Our finding that CA-S6K1 transfection enhanced *TGFβ1* gene transactivation, whereas that with DN-S6K1 transfection inhibited it, provides compelling evidence that S6K1 activity is directly associated with the gene regulation. Furthermore, the result of reporter gene analysis showing that *TGFβ1* gene repression by PGJ_2 + RA was completely reversed by CA-S6K1 lends support to the conclusion that S6K1 inhibition by PGJ_2 + RA is responsible for *TGFβ1* gene regulation. In addition to the ligand activation of nuclear receptors, we were able to show that ectopic expression of PPARγ1 or RXRα alone, or in combination, was capable of repressing *TGFβ1* gene with S6K1 inhibition. Furthermore, CA-S6K1 transfection completely reversed *TGFβ1* gene inhibition by PPARγ + RXRα. These observations led us to conclude that PPARγ-RXR heterodimer activation results in *TGFβ1* gene repression via S6K1 inhibition. Inhibition of S6K1 activity provides a central mechanism, by which PPARγ-RXR regulates Zf9-dependent *TGFβ1* gene expression.

One of the target genes, whose promoter region contains PPRE(s) for PPARγ-RXRα-dependent gene induction, is PTEN (Patel et al., 2001). PTEN serves as a phosphatidylinositol-(3,4,5)-trisphosphate lipid phosphatase, which antagonizes PI3-kinase-mediated signaling cascade. Thus, PTEN expression inhibited cell signals such as mTOR-S6K1 activity downstream of PI3-kinase (Liu et al., 2005). PPARγ activation up-regulates PTEN, which has been implicated in tumor-inhibitory or anti-inflammatory actions of PPARγ (Patel et al., 2001; Lee et al., 2005). Our significant finding that PGJ_2 + RA induced PTEN during the period of S6K1 inhibition gives credence to the role of PPARγ-RXR-mediated PTEN expression in S6K1 inhibition. These data along with the observation that PTEN overexpression inhibits S6K1 activity with *TGFβ1* repression render us to conclude that PPARγ-RXRα heterodimer leads to the inhibition of S6K1 activity as a result of PPRE-mediated PTEN induction, which seemed to be mediated by the pathways of ERK1/2-RSK1 and Akt-mTOR (Fig. 9).

In summary, PPARγ-RXRα heterodimer, which up-regulates PTEN, represses the *TGFβ1* gene by inhibiting the activity of S6K1 that catalyzes Zf9 phosphorylation. Phosphorylated Zf9 may serve as an essential component that recruits coactivator, which is an important question to answer in the future.

References

Biecker E, De Gottardi A, Neef M, Unternahrer M, Schneider V, Ledermann M, Sagesser H, Shaw S, and Reichen J (2005) Long-term treatment of bile duct-ligated rats with rapamycin (sirolimus) significantly attenuates liver fibrosis: analysis of the underlying mechanisms. *J Pharmacol Exp Ther* **313:**952–961.

Chawla A, Schwarz EJ, Dimaculangan DD, and Lazar MA (1994) Peroxisome proliferator-activated receptor (PPAR) gamma: adipose-predominant expression and induction early in adipocyte differentiation. *Endocrinology* **135:**798–800.

Chung JK, Kuo CJ, Crabtree GR, and Blenis J (1992) Rapamycin-FKBP specifically blocks growth-dependent activation of and signaling by the 70 kD S6 protein kinases. *Cell* **69:**1227–1236.

de Groot RP, Ballou LM, and Sassone-Corsi P (1994) Positive regulation of the cAMP-responsive activator CREM by the p70 S6 kinase: an alternative route to mitogen-induced gene expression. *Cell* **79:**81–91.

Dubuquoy L, Dharancy S, Nutten S, Pettersson S, Auwerx J, and Desreumaux P (2002) Role of peroxisome proliferator-activated receptor gamma and retinoid X receptor heterodimer in hepatogastroenterological diseases. *Lancet* **360:**1410–1418.

Friedman SL (1993) Seminars in medicine of the Beth Israel Hospital, Boston. The cellular basis of hepatic fibrosis. Mechanisms and treatment strategies. *N Engl J Med* **328:**1828–1835.

Hannan KM, Brandenburger Y, Jenkins A, Sharkey K, Cavanaugh A, Rothblum L, Moss T, Poortinga G, McArthur GA, Pearson RB, et al. (2003) mTOR-dependent regulation of ribosomal gene transcription requires S6K1 and is mediated by phosphorylation of the carboxy-terminal activation domain of the nucleolar transcription factor UBF. *Mol Cell Biol* **23:**8862–8877.

Harada H, Andersen JS, Mann M, Terada N, and Korsmeyer SJ (2001) p70S6 kinase signals cell survival as well as growth, inactivating the pro-apoptotic molecule BAD. *Proc Natl Acad Sci USA* **98:**9666–9670.

Hazra S, Xiong S, Wang J, Rippe RA, Krishna V, Chatterjee K, and Tsukamoto H (2004) Peroxisome proliferator-activated receptor gamma induces a phenotypic switch from activated to quiescent hepatic stellate cells. *J Biol Chem* **279:**11392–11401.

Holmbeck SM, Foster MP, Casimiro DR, Sem DS, Dyson HJ, and Wright PE (1998) High-resolution solution structure of the retinoid X receptor DNA-binding domain. *J Mol Biol* **281:**271–284.

IJpenberg A, Jeannin E, Wahli W, and Desvergne B (1997) Polarity and specific sequence requirements of peroxisome proliferator-activated receptor (PPAR)/retinoid X receptor heterodimer binding to DNA. A functional analysis of the malic enzyme gene PPAR response element. *J Biol Chem* **272:**20108–20117.

Jeno P, Ballou LM, Novak-Hofer I, and Thomas G (1988) Identification and characterization of a mitogen-activated S6 kinase. *Proc Natl Acad Sci USA* **85:**406–410.

Kamei Y, Xu L, Heinzel T, Torchia J, Kurokawa R, Gloss B, Lin SC, Heyman RA, Rose DW, Glass CK, et al. (1996) A CBP integrator complex mediates transcriptional activation and AP-1 inhibition by nuclear receptors. *Cell* **85:**403–414.

Kang KW, Choi SH, Ha JR, Kim CW, and Kim SG (2002) Inhibition of dimethylnitrosamine-induced liver fibrosis by [5-(2-pyrazinyl)-4-methyl-1,2-dithiol-3-thione] (oltipraz) in rats: suppression of transforming growth factor-beta1 and tumor necrosis factor-alpha expression. *Chem Biol Interact* **139:**61–77.

Kim SJ, Angel P, Lafyatis R, Hattori K, Kim KY, Sporn MB, Karin M, and Roberts AB (1990) Autoinduction of transforming growth factor beta 1 is mediated by the AP-1 complex. *Mol Cell Biol* **10:**1492–1497.

Kim SJ, Glick A, Sporn MB, and Roberts AB (1989a) Characterization of the promoter region of the human transforming growth factor-beta 1 gene. *J Biol Chem* **264:**402–408.

Kim SJ, Jeang KT, Glick AB, Sporn MB, and Roberts AB (1989b) Promoter sequences of the human transforming growth factor-beta 1 gene responsive to transforming growth factor-beta 1 autoinduction. *J Biol Chem* **264:**7041–7045.

Kim Y, Ratziu V, Choi SG, Lalazar A, Theiss G, Dang Q, Kim SJ, and Friedman SL (1998) Transcriptional activation of transforming growth factor beta1 and its receptors by the Kruppel-like factor Zf9/core promoter-binding protein and Sp1. Potential mechanisms for autocrine fibrogenesis in response to injury. *J Biol Chem* **273:**33750–33758.

Kliewer SA, Umesono K, Noonan DJ, Heyman RA, and Evans RM (1992) Convergence of 9-cis retinoic acid and peroxisome proliferator signalling pathways through heterodimer formation of their receptors. *Nature (Lond)* **358:**771–774.

Kon K, Ikejima K, Hirose M, Yoshikawa M, Enomoto N, Kitamura T, Takei Y, and Sato N (2002) Pioglitazone prevents early-phase hepatic fibrogenesis caused by carbon tetrachloride. *Biochem Biophys Res Commun* **291:**55–61.

Kruse JJ, Bart CI, Leer JW, and Wondergem J (1999) Detection and quantitative measurement of transforming growth factor-beta1 (TGF-beta1) gene expression using a semi-nested competitive PCR assay. *Cytokine* **11:**179–185.

Lee KS, Park SJ, Hwang PH, Yi HK, Song CH, Chai OH, Kim JS, Lee MK, and Lee YC (2005) PPAR-gamma modulates allergic inflammation through up-regulation of PTEN. *FASEB J* **19:**1033–1035.

Lee KY, Ito K, Hayashi R, Jazrawi EP, Barnes PJ, and Adcock IM (2006) NF-kappaB and activator protein 1 response elements and the role of histone modifications in IL-1beta-induced TGF-beta1 gene transcription. *J Immunol* **176:**603–615.

Liu JL, Sheng X, Hortobagyi ZK, Mao Z, Gallick GE, and Yung WK (2005) Nuclear PTEN-mediated growth suppression is independent of Akt down-regulation. *Mol Cell Biol* **25:**6211–6224.

Marra F, DeFranco R, Robino G, Novo E, Efsen E, Pastacaldi S, Zamara E, Vercelli A, Lottini B, Spirli C, et al. (2005) Thiazolidinedione treatment inhibits bile duct proliferation and fibrosis in a rat model of chronic cholestasis. *World J Gastroenterol* **11:**4931–4938.

Marra F, Efsen E, Romanelli RG, Caligiuri A, Pastacaldi S, Batignani G, Bonacchi A, Caporale R, Laffi G, Pinzani M, et al. (2000) Ligands of peroxisome proliferator-activated receptor gamma modulate profibrogenic and proinflammatory actions in hepatic stellate cells. *Gastroenterology* **119:**466–478.

Mukherjee R, Jow L, Croston GE, and Paterniti JR Jr (1997) Identification, characterization and tissue distribution of human peroxisome proliferator-activated receptor (PPAR) isoforms PPARgamma2 versus PPARgamma1 and activation with retinoid X receptor agonists and antagonists. *J Biol Chem* **272:**8071–8076.

Narla G, Heath KE, Reeves HL, Li D, Giono LE, Kimmelman AC, Glucksman MJ, Narla J, Eng FJ, Chan AM, et al. (2001) KLF6, a candidate tumor suppressor gene mutated in prostate cancer. *Science (Wash DC)* **294:**2563–2566.

Oklu R and Hesketh R (2000) The latent transforming growth factor beta binding protein (LTBP) family. *Biochem J* **352:**601–610.

Park EY, Cho IJ, and Kim SG (2004) Transactivation of the PPAR-responsive enhancer module in chemopreventive glutathione S-transferase gene by the peroxisome proliferator-activated receptor-gamma and retinoid X receptor heterodimer. *Cancer Res* **64:**3701–3713.

Patel L, Pass I, Coxon P, Downes CP, Smith SA, and Macphee CH (2001) Tumor suppressor and anti-inflammatory actions of PPARgamma agonists are mediated via upregulation of PTEN. *Curr Biol* **11:**764–768.

Pesce L, Comellas A, and Sznajder JI (2003) Beta-adrenergic agonists regulate Na-K-ATPase via p70S6K. *Am J Physiol* **285:**L802–L807.

Ratziu V, Lalazar A, Wong L, Dang Q, Collins C, Shaulian E, Jensen S, and Friedman SL (1998) Zf9, a Kruppel-like transcription factor up-regulated in vivo during early hepatic fibrosis. *Proc Natl Acad Sci USA* **95:**9500–9505.

Salbert G, Fanjul A, Piedrafita FJ, Lu XP, Kim SJ, Tran P, and Pfahl M (1993) Retinoic acid receptors and retinoid X receptor-alpha down-regulate the transforming growth factor-beta 1 promoter by antagonizing AP-1 activity. *Mol Endocrinol* **7:**1347–1356.

Skinner HD, Zheng JZ, Fang J, Agani F, and Jiang BH (2004) Vascular endothelial growth factor transcriptional activation is mediated by hypoxia-inducible factor 1α, HDM2 and p70S6K1 in response to phosphatidylinositol 3-kinase/AKT signaling. *J Biol Chem* **279:**45643–45651.

Slavin DA, Koritschoner NP, Prieto CC, Lopez-Diaz FJ, Chatton B, and Bocco JL (2004) A new role for the Kruppel-like transcription factor KLF6 as an inhibitor of c-Jun proto-oncoprotein function. *Oncogene* **23:**8196–8205.

Wang X, Li W, Williams M, Terada N, Alessi DR, and Proud CG (2001) Regulation of elongation factor 2 kinase by p90(RSK1) and p70 S6 kinase. *EMBO (Eur Mol Biol Organ) J* **20:**4370–4379.

Warke VG, Nambiar MP, Krishnan S, Tenbrock K, Geller DA, Koritschoner NP, Atkins JL, Farber DL, and Tsokos GC (2003) Transcriptional activation of the human inducible nitric-oxide synthase promoter by Kruppel-like factor 6. *J Biol Chem* **278:**14812–14819.

Weigert C, Brodbeck K, Bierhaus A, Haring HU, and Schleicher ED (2003) c-Fos-driven transcriptional activation of transforming growth factor beta-1: inhibition of high glucose-induced promoter activity by thiazolidinediones. *Biochem Biophys Res Commun* **304:**301–307.

Weigert C, Sauer U, Brodbeck K, Pfeiffer A, Haring HU, and Schleicher ED (2000) AP-1 proteins mediate hyperglycemia-induced activation of the human TGF-beta1 promoter in mesangial cells. *J Am Soc Nephrol* **11:**2007–2016.

Zhang XK, Hoffmann B, Tran PB, Graupner G, and Pfahl M (1992) Retinoid X receptor is an auxiliary protein for thyroid hormone and retinoic acid receptors. *Nature (Lond)* **355:**441–446.

Zhu J, Wu J, Frizell E, Liu SL, Bashey R, Rubin R, Norton P, and Zern MA (1999) Rapamycin inhibits hepatic stellate cell proliferation in vitro and limits fibrogenesis in an in vivo model of liver fibrosis. *Gastroenterology* **117:**1198–1204.

Address correspondence to: Dr. Sang Geon Kim, College of Pharmacy, Seoul National University, Sillim-dong, Kwanak-gu, Seoul 151-742, Korea. E-mail: sgk@snu.ac.kr