Acyclic Retinoid Targets Platelet-Derived Growth Factor Signaling in the Prevention of Hepatic Fibrosis and Hepatocellular Carcinoma Development

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Abstract

Hepatocellular carcinoma (HCC) often develops in association with liver cirrhosis, and its high recurrence rate leads to poor patient prognosis. Although recent evidence suggests that peretinoin, a member of the acyclic retinoid family, may be an effective chemopreventive drug for HCC, published data about its effects on hepatic mesenchymal cells, such as stellate cells and endothelial cells, remain limited. Using a mouse model in which platelet-derived growth factor (PDGF)-C is overexpressed (Pdgf-c Tg), resulting in hepatic fibrosis, steatosis, and eventually, HCC development, we show that peretinoin significantly represses the development of hepatic fibrosis and tumors. Peretinoin inhibited the signaling pathways of fibrogenesis, angiogenesis, and Wnt/β-catenin in Pdgf-c transgenic mice. In vitro, peretinoin repressed the expression of PDGF receptors α/β in primary mouse hepatic stellate cells (HSC), hepatoma cells, fibroblasts, and endothelial cells. Peretinoin also inhibited PDGF-C–activated transformation of HSCs into myofibroblasts. Together, our findings show that PDGF signaling is a target of peretinoin in preventing the development of hepatic fibrosis and HCC. Cancer Res; 72(17); 4459–71. ©2012 AACR.

Introduction

Hepatocellular carcinoma (HCC) is one of the most common malignancies worldwide with a particularly poor patient outcome (1). It often develops as a result of chronic liver disease associated with hepatitis B or hepatitis C virus infection or with other etiologies such as long-term alcohol abuse, autoimmunity, and hemochromatosis (2–5). Despite the recent advances in antiviral therapy for hepatitis B or hepatitis C virus, these are insufficient to completely prevent the occurrence of HCC. Moreover, the recent increase in nonalcoholic fatty liver disease (NAFLD) associated with metabolic syndrome is a potential high-risk factor for the development of HCC (6).

HCC often develops during the advanced stages of liver fibrosis and is associated with deposits of extracellular matrix synthesized by activated stellate cells. During the course of chronic hepatitis, nonparenchymal cells, including Kupffer, endothelial, and activated stellate cells, release a variety of cytokines and growth factors. One of these growth factors is platelet-derived growth factor (PDGF), which is involved in fibrogenesis, angiogenesis, and tumorigenesis (7, 8). PDGF expression has been shown to be upregulated from the early stages of chronic hepatitis, suggesting its association with the development of fibrosis in chronic hepatitis C (CH-C; refs. 9 and 10). Overexpression of PDGF-C in mouse liver resulted in the progression of hepatic fibrosis, steatosis, and the development of HCC; this mouse model closely resembles the human HCC, which is frequently associated with hepatic fibrosis (7).

Peretinoin (generic name; code, NIK-333), developed by the Kowa Company, is an oral acyclic retinoid with a vitamin A–like structure, which targets the retinoid nuclear receptor. Oral administration of peretinoin was shown to significantly reduce the incidence of posttherapeutic HCC recurrence and improve the survival rates of patients in a clinical trial (11, 12). A large-scale clinical study including various countries is now planned to confirm its clinical efficacy.

Although peretinoin treatment can suppress HCC-derived cell line growth and inhibit experimental mouse or rat liver carcinogenesis (13, 14), the detailed mechanism of its effect has not been fully elucidated. Peretinoin has a high binding affinity to cellular retinoic acid-binding protein (15) and may interact with retinoic acid receptor-β and retinoid X receptor-α (16); however, the precise molecular targets for preventing HCC recurrence have not yet been elucidated.
In this study, we used PDGF-C transgenic (Pdgf-c Tg) mice to show that PDGF-C signaling is a possible target of peretinoin in the prevention of hepatic fibrosis, angiogenesis, and the development of HCC.

Materials and Methods

Chemicals
The acyclic retinoid peretinoin (generic name; code, NIK-333) [(2E,4E,6E,10E)-3,7,11,15-tetramethyl-2,4,6,10,14-hexadecapentaenoic acid, C20H30O2, molecular weight 302.46 g/mol] was supplied by Kowa Company.

Animal studies
The generation and characterization of Pdgf-c Tg have been described previously (7). Wild-type and Pdgf-c Tg mice on a C57BL/6J background were maintained in a pathogen-free animal facility under standard 12-hour/12-hour light/dark cycle. After weaning at week 4, male mice were randomly divided into the following 3 groups: (1) Pdgf-c Tg or wild-type (WT) mice given a basal diet (CRF-1, Charles River Laboratories Japan), (2) Pdgf-c Tg or WT mice given a 0.03% peretinoin-containing diet, (3) Pdgf-c Tg or WT mice given a 0.06% peretinoin-containing diet. Control mice were normal male homozygotes. At week 20, mice were sacrificed to analyze the progression of hepatic fibrosis (n = 15 for each of the 3 groups). At week 48, mice were sacrificed to analyze the development of hepatic tumors (n = 31 for the basal diet group, n = 37 for the 0.03% peretinoin group, and n = 17 for the 0.06% peretinoin group). The incidence of hepatic tumors, maximum tumor size, and liver weight were evaluated. None of the treated WT mice given a diet of 0.03% peretinoin died, but death occurred in 5% of WT mice around after 36 weeks of age receiving a 0.06% peretinoin diet, probably because of its toxicity. In Pdgf-c Tg mice, death was observed at similar frequency as WT mice that received 0.06% peretinoin diet.

All animal experiments were carried out in accordance with Guidelines for the Care and Use of Laboratory Animals at the Takara-Machi Campus of Kanazawa University, Japan.

Cell culture
Human HCC cell lines Huh-7, HepG2, and HLE, the mouse fibroblast cell line NIH3T3, human umbilical vein endothelial cells (HUVEC), and human stellate cells LX-2 (kindly provided by Dr. Scott Friedman, Mount Sinai School of Medicine, New York, NY) were maintained in Dulbecco’s Modified Eagle Medium (DMEM; Gibco) supplemented with 10% FBS (Gibco), 1% L-glutamine (Gibco), and 1% penicillin/streptomycin (Gibco) in a humidified atmosphere of 5% CO2 at 37°C. 1 to 5 × 106 cells were seeded in each well of a 12-well plate the day before serum starvation in serum-free DMEM for 8 hours. The culture medium was then replaced with serum-free medium containing peretinoin. After 24-hour incubation, cells were harvested for analysis.

Isolation and culture of mouse hepatic stellate cells
Hepatic stellate cells (HSC) were isolated from C57BL/6J mice and the effect of recombinant human PDGF-C and peretinoin on HSCs was evaluated in vitro. Pronase-collagenase liver digestion was used to isolate HSC from wild-type mice. All experiments were replicated at least twice. freshly isolated HSCs suspended in culture medium were seeded in uncoated 24-well plates and incubated at 37°C in a humidified atmosphere of 5% CO2 for 72 hours. Nonadherent cells were removed with a pipette and the culture medium was replaced with medium containing 80 ng/mL recombinant human PDGF-C (Abnova) with or without peretinoin or 9-cis-retinoic acid (9cRA; 5 or 10 μmol/L). Cells were harvested for analysis after 24-hour incubation.

Isolation of peripheral blood mononuclear cells
Peripheral blood mononuclear cells were harvested and labeled with FITC-conjugate CD34 (Cell Lab) and R-Phycocerythrin (PE)-conjugated CD31 antibodies (Cell Lab) for 30 minutes at 4°C. After washing with 1 mL PBS, CD31 and CD34 surface expression was measured with a FACSCalibur flow cytometer (BD Biosciences). All flow cytometric data were analyzed using FlowJo software (Tree Star).

Gene expression profiling
Gene expression profiling in mouse liver was evaluated using the GeneChip Mouse Genome 430 2.0 Array (Affymetrix). Liver tissue from WT, Pdgf-c Tg, and Pdgf-c Tg with 0.06% peretinoin mice all at weeks 20 and 48 was obtained and a total of 34 chip assays were conducted as described previously (17). Expression data have been deposited in the Gene Expression Omnibus (GEO; NCBI Accession: GSE31431).

Pathway analysis was conducted using MetaCore (GeneGo). Functional ontology enrichment analysis was conducted to compare the Gene Ontology (GO) process distribution of differentially expressed genes (P < 0.01; refs. 10 and 17). Direct interactions among differentially expressed genes between Pdgf-c Tg mice with or without peretinoin administration were examined as reported previously (10). Each connection represents a direct, experimentally confirmed, physical interaction (MetaCore).

Histopathology and immunohistochemical staining
Mouse liver tissues were fixed in 10% formalin and stained with hematoxylin and eosin. The liver neoplasms (HCC and liver cell adenoma) were diagnosed according to previously described criteria (18, 19). Hepatic fibrosis was evaluated by Azan staining. Percentages of fibrous areas were calculated microscopically using an image analysis system (BIORVEO BZ-9000: KEYENCE Japan). Immunohistochemical (IHC) staining was conducted by an immunoperoxidase technique with an Envision kit (DAKO). Primary antibodies used were: rabbit polyclonal PDGFR-α (1:100 dilution), PDGFR-β (1:100 dilution), VEGFR1 (1:100 dilution), desmin (1:100 dilution), β-catenin (1:200 dilution), and mouse monoclonal cyclin D1 (1:400 dilution; all from Cell Signaling Technology); collagen 1 (1:100 dilution), collagen 4 (1:100 dilution), CD31 (1:100 dilution), and CD34 (1:100 dilution; all from Abcam, Cambridge, MA); and Tie-2 (1:80 dilution) and Myc (1:100 dilution; both from Santa Cruz Biotechnology).
**Quantitative real-time detection PCR**

Total RNA was isolated from frozen liver tissue samples using a GenElute Mammalian Total RNA Miniprep Kit (Sigma-Aldrich) according to the manufacturer’s protocol. cDNA was synthesized from 100 ng total RNA using a high-capacity cDNA reverse transcription kit (Applied Biosystems) then mixed with the TaqMan Universal Master Mix (Applied Biosystems) and each TaqMan probe. TaqMan probes used were PDGFR-α/β, VEGFR1/2, α-SMA, collagen 1/4, β-catenin, CyclinD1, and Myc (Applied Biosystems). Relative expression levels were calculated after normalization to glyceraldehyde-3-phosphate dehydrogenase (GAPDH).

**Western blotting**

Western blotting was conducted as described previously (20). Whole-cell lysates from mouse liver were prepared and lysed by Celllytic MT cell lysis reagent (Pierce Biotechnology). Cytoplasmic and nuclear protein extracts were prepared using the NE-PER nuclear extraction reagent kit (Pierce Biotechnology). Primary antibodies used were PDGFR-α (1:1,000 dilution), PDGFR-β (1:1,000 dilution), VEGFR2 (1:1,000 dilution), p44/42 MAPK (1:1,000 dilution), total AKT (1:1,000 dilution), p-p44/42 MAPK (1:1,000 dilution), p-AKT (Ser473; 1:1,000 dilution), p-AKT (Thr308; 1:1,000 dilution), β-catenin (1:2,000 dilution), cycdin D1 (1:400 dilution), and lamin A/C (1:1,000 dilution; all Cell Signaling Technology); 4-HNE (1:200 dilution; NOF); α-SMA (1:200 dilution; DAKO); -SMA, and desmin was significantly upregulated in Pdgf-c Tg mice, but repressed by peretinoin (Fig. 2 and Supplementary Fig. S1A).

**Statistical analysis**

Results are expressed as mean ± SD. Significance was tested by 1-way analysis of variance with Bonferroni’s method, and differences were considered statistically significant at P < 0.05.

**Results**

**Peretinoin prevented the development of hepatic fibrosis in Pdgf-c Tg mice**

To evaluate the HCC chemopreventive effects of peretinoin, we used a mouse model of Pdgf-c Tg in which PDGF-C is expressed under the control of the albumin promoter (7). Experimental mice were male mice expressing the PDGF-C transgene (Pdgf-c Tg); whereas male mice not expressing the transgene were considered WT. After weaning at week 4, Pdgf-c Tg or nontransgenic WT mice were fed a basal diet or a diet containing 0.03% or 0.06% peretinoin. At week 20, mice were sacrificed to analyze the progression of hepatic fibrosis. At week 48, mice were sacrificed to analyze the development of hepatic tumors (Fig. 1A). At week 20, Azan staining showed that predominant pericellular fibrosis had developed in Pdgf-c Tg mice (Fig. 1B). Densitometric analysis showed a significant dose-dependent reduction in the size of the fibrotic area in mice that received a diet containing peretinoin at both weeks 20 and 48 (Fig. 1C). Peretinoin therefore efficiently repressed the development of hepatic fibrosis in Pdgf-c Tg mice.

The expression of fibrosis-related genes in Pdgf-c Tg mice was evaluated by IHC staining, quantitative real-time detection PCR (RTD-PCR), and Western blotting. The expression of PDGFR-α and PDGFR-β, essential receptors for intracellular PDGF-C signaling, was upregulated mainly in the intracellular or portal area in Pdgf-c Tg mice livers (Fig. 2), but was significantly repressed by peretinoin after weaning at week 4. Similarly, the expression of collagen 1, collagen 4, and desmin was significantly upregulated in Pdgf-c Tg mice, but repressed by peretinoin (Fig. 2 and Supplementary Fig. S1A).

RTD-PCR results confirmed that these genes were substantially upregulated in Pdgf-c Tg mice and significantly repressed by both 0.03% and 0.06% peretinoin (Fig. 3A). Western blotting showed that the expression of phosphorylated extracellular signal-regulated kinase (p-ERK) 1/2 and cyclin D1, representative markers of the cell proliferation signaling pathway, was upregulated in Pdgf-c Tg mice, and repressed by peretinoin (Fig. 3B). Thus, peretinoin could partially but significantly prevent the development of hepatic fibrosis in Pdgf-c Tg mice during the study observation period of 48 weeks.

**Peretinoin prevented the development of HCC in Pdgf-c Tg mice**

At week 48, Pdgf-c Tg mice developed hepatic tumors with an incidence of 90% (Fig. 4A). Histologic assessment of these tumors verified that 54% (15/28) were adenomas and 46% (13/28) were HCC (Fig. 4A and C and Supplementary Fig. S2; ref. 21). Peretinoin (0.03%) dose-dependently repressed the incidence of hepatic tumors to 53% (19/36) and to 29% (5/17) at 0.06%. Correlating with tumor incidence, maximum tumor size and liver weight were also significantly repressed by peretinoin (Fig. 4B). Thus, peretinoin repressed the development of hepatic tumors in Pdgf-c Tg mice.

**Serial gene expression profiling in the liver of Pdgf-c Tg mice that developed hepatic fibrosis and tumors**

To examine which signaling pathways were altered during the progression of hepatic fibrosis and tumor development, we analyzed gene expression profiling in the liver of Pdgf-c Tg mice using Affymetrix gene chips. By filtering criteria for P < 0.001 and more than 2-fold differences, 538 genes were selected as differentially expressed. One-way hierarchical clustering analysis of differentially expressed genes is shown in Supplementary Fig. S3.

Of the 3 main clusters, 2 were upregulated (clusters A and B) and 1 was downregulated (cluster C). Cluster A consisted of immune-related [chemokine (C-C motif) receptor (CCR)4, CCR2, toll-like receptor (TLR)3 and TLR4], apoptosis-related [caspase (CASP)1 and CASP9], angiogenesis- and/or growth factor-related (PDGF-C, VEGF-C, osteopontin, HGF), oncogene-related [v-ets erythroblastosis virus E26 oncogene homologue (Ets)], Ets2, CD44, N-myc downstream-regulated (NDRG)1], and fibrosis-related (tubulin) genes. The expression of cluster A genes was further upregulated in tumors at week...
Cluster B consisted mainly of connective tissue- and/or fibrosis-related [vascular cell adhesion molecule (VCAM)1, collagen I, III, IV, V, VI, integrin, decorin, TGF-βRII, PDGFR-α, and PDGFR-β] genes, the expression of which declined slightly at week 48. In contrast, cluster C, containing differentiation and liver function related genes [cytochrome P450, family 2, subfamily c (CYP2C)], were downregulated during the course of hepatic fibrosis and tumor development (Supplementary Fig. S4). Cluster C included xenobiotic- and metabolic process-related genes, which are potential targets of peretinoin. Peretinoin treatment prevented hepatic fibrosis and it preserved liver function. In addition, peretinoin might induce its target genes. Thus, peretinoin reduced the expression of upregulated genes (clusters A and B) and restored the expression of downregulated genes (cluster C) at both weeks 20 and 48 (Supplementary Figs. S3 and S4).
To examine the molecular network consisting of differentially expressed genes in Pdgf-c Tg mice with or without peretinoin administration, the direct interactions of 513 genes were analyzed by MetaCore (i.e., 413 genes were downregulated and 100 genes were upregulated in Pdgf-c Tg mice treated with peretinoin compared with untreated mice; \( P < 0.002 \)). A core gene network consisting of 41 genes was obtained (Supplementary Fig. S5) including interactions between representative growth factors, receptors (PDGFR and TGF\(\beta\)R), and transcriptional factors. Of these genes, the transcriptional factors Sp1 and Ap1 seem to be key regulators in the network (Supplementary Fig. S5).

**Peretinoin inhibits PDGFR in vitro**

Gene expression profiling landscaped the dynamic changes of signaling pathways in Pdgf-c Tg mice. To determine the effects of peretinoin in vitro, primary HSCs from normal C57BL/6j mice were stimulated by PDGF-C (Fig. 5) to induce the expression of PDGFR-\(\alpha\), PDGFR-\(\beta\), alpha smooth muscle actin (\(\alpha\)-SMA), and collagen 1a2; activated HSCs thus transformed into myofibroblasts (Fig. 5A and B). Peretinoin significantly reduced the expression of these genes and inhibited HSC activation.

We next evaluated the effects of peretinoin on human hepatoma cell lines (Huh-7, HepG2, and HLE), mouse embryonic fibroblast cells (NH3T3), HUVECs, and Lx-2 (ref. 22; Supplementary Fig. S6A). Experimental conditions were optimized so that more than 90% of cells were variable at 20 \( \mu \)mol/L peretinoin, as determined by an MTS cell proliferation assay (data not shown). Peretinoin dose-dependently inhibited the expression of PDGFR-\(\alpha\) and PDGFR-\(\beta\) in Huh-7, HepG2, HLE, NH3T3, HUVEC, and Lx-2 cells, whereas no obvious expression of PDGFR-\(\alpha\) was observed in HepG2 cells and HUVECs (Supplementary Fig. S6A). Peretinoin also inhibited VEGFR2 expression in HUVEC. These results were confirmed by RTD-PCR (data not shown). Correlating with these results, the expression of phosphorylated serine/threonine kinase AKT (p-AKT) and p-ERK1/2, downstream signaling molecules of PDGFR-\(\alpha\), PDGFR-\(\beta\), and VEGFR2, was also dose-dependently repressed. The expression of collagen 1a2 was significantly repressed by peretinoin in Lx-2, HLE, and Huh-7 cells (Supplementary Fig. S6B). These results suggest that peretinoin may inhibit hepatic fibrosis, angiogenesis, and tumor growth through reduction of the PDGF and VEGF signaling pathway.

We examined the expression of 2 key regulators in peretinoin signaling, Sp1 and Ap1, in Huh-7 cells. Interestingly, the expression of Sp1 was decreased, which correlates with that of PDGFR-\(\alpha\), whereas expression of phosphorylated c-Jun (p-c-Jun) was increased in Huh-7 cells (Supplementary Fig. S6C). Therefore, peretinoin seems to repress the expression of PDGFR, partially through the inhibition of Sp1.

**Peretinoin inhibits hepatic angiogenesis in Pdgf-c Tg mice**

The effect of peretinoin on liver angiogenesis in Pdgf-c Tg mice was further analyzed. IHC staining of Pdgf-c Tg mouse
livers at weeks 20 and 48 revealed overexpression of the endothelial markers CD31 and CD34 and the endothelial growth factors VEGFR1 and endothelium-specific receptor tyrosine kinase 2 (Tie2) in the mesenchymal region (Fig. 6 and Supplementary Fig. S1A). This expression was significantly repressed by peretinoin as determined by the densitometric area (Supplemental Fig. S1B). RTD-PCR results revealed significant upregulation of VEGFR1 (Flt-1) in Pdgf-c Tg mice compared with WT mice at both weeks 20 and 48, whereas the expression of VEGFR2 (Flk-1) and Tie2 was only upregulated at week 48. The expression of these genes was significantly repressed by peretinoin (Fig. 6A). Western blotting confirmed the upregulation of CD31 and VEGFR1 (Flk-1) at week 48 (Fig. 6B). In addition, p-AKT (Thr 308 and Ser 473) and 4-hydroxy-2-nonenal (4-HNE), an oxidative stress marker, were upregulated in Pdgf-c Tg mice and repressed by peretinoin (Fig. 6B).

We also assessed circulating endothelial cells (CEC), a useful biomarker for angiogenesis in the blood, and found that the CD31<sup>+</sup>/CD34<sup>+</sup> CEC population was significantly upregulated in Pdgf-c Tg mice at week 48 but significantly repressed by peretinoin (Fig. 6C and D). Thus, peretinoin
seems to inhibit angiogenesis in the liver of Pdgf-c Tg mice, which might prevent the development of hepatic tumors.

**Peretinoin inhibits canonical Wnt/β-catenin signaling in Pdgf-c Tg mice**

The activation of the Wnt/β-catenin signaling pathway is seen in 17% to 40% of patients with primary HCC (23, 24). Moreover, recent reports suggested an interaction between PDGF signaling and Wnt/β-catenin signaling (25–27). We evaluated Wnt/β-catenin signaling in Pdgf-c Tg mice and showed by IHC staining that β-catenin was overexpressed in the submembrane at week 48 (Fig. 7A). Peretinoin significantly reduced this expression (Fig. 7A and B), and Western blotting revealed that accumulation of β-catenin in the nuclear fraction of liver tumor tissues was more preferentially repressed by peretinoin than in the cytoplasmic fraction, although expression was repressed in both fractions (Fig. 7C). Wnt ligand (Wnt5a) and frizzled receptor (Fzd1) expression was significantly upregulated in hepatic tumors compared with normal liver (Fig. 7D). These results together suggest that canonical Wnt/β-catenin...
signaling is activated in hepatic tumors and repressed by peretinoin.

Growth factors such as PDGF or HGF potentially activate Wnt/β-catenin signaling (26, 28), which promotes cancer progression and metastasis. We evaluated whether such growth factor signaling could be repressed by peretinoin in hepatic tumors. The expression of c-myc, β-catenin, Tie2, Fit-1, and Flk-1 were significantly upregulated from 1.5- to 4-fold in hepatic tumors compared with normal liver, and this expression was significantly repressed by peretinoin. Similarly, the expression of PDGFR-α, PDGFR-β, collagen 1a2, collagen 4a2, tissue inhibitor of metalloproteinase 2 (TIMP2), and cyclin D1 was substantially upregulated from 5- to 15-fold in hepatic tumors, and significantly repressed by peretinoin (Fig. 7D). Thus, growth factor signaling as well as canonical Wnt/β-catenin signaling in hepatic tumors seems to be repressed by peretinoin. These results explain the inhibitory effect of peretinoin in the development of HCC in Pdgf-c Tg mice.

Discussion

HCC often develops in association with liver cirrhosis and its high recurrence rate leads to poor patient prognosis. Indeed, the 10-year recurrence-free survival rate after liver resection for HCC with curative intent was shown to be only 20% (29). Therefore, there is a pressing need to develop effective preventive therapy for HCC recurrence to improve its prognosis.

Peretinoin, a member of the acyclic retinoid family, is expected to be an effective chemopreventive drug for HCC (11, 12, 30) as shown by a previous phase II/III trial in which 600 mg peretinoin per day in the Child-Pugh A subgroup reduced the risk of HCC recurrence or death by 40% [HR = 0.60 (95% CI, 0.40–0.89); ref. 31]. However, further clinical
studies are needed to confirm the clinical efficacy of peretinoin, and a large scale study involving several countries is currently being planned.

During the course of chronic hepatitis, nonparenchymal cells including Kupffer, endothelial and activated stellate cells release a variety of cytokines and growth factors that might accelerate hepatocarcinogenesis. Although peretinoin has been shown to suppress the growth of HCC-derived cells by inducing apoptosis and differentiation (32–35), increasing p21 and reducing cyclin D1 (13), limited data have been published about its effects on hepatic mesenchymal cells such as stellate cells and endothelial cells (14).

In parallel with a phase II/III trial, we conducted a pharmacokinetics study of peretinoin focusing on 12
patients with CH-C and HCC to monitor the biological behavior of peretinoin in the liver. Gene expression profiling during peretinoin administration revealed that HCC recurrence within 2 years could be predicted and that PDGF-C expression was one of the strongest predictors. In addition, other genes related to angiogenesis, cancer stem cell and tumor progression were downregulated, whereas expression of genes related to hepatocyte differentiation and tumor suppression was upregulated by peretinoin (data not shown). Moreover, a recent report revealed the emerging significance of PDGF-C-mediated angiogenic and tumorogenic properties (7, 8, 36). In this study, we therefore used the mouse model of Pdgf-c Tg, which displays the phenotypes of hepatic fibrosis, steatosis, and HCC development that resemble human HCC arising from chronic hepatitis usually associated with advanced hepatic fibrosis.

We showed that peretinoin effectively inhibits the progression of hepatic fibrosis and tumors in Pdgf-c Tg mice (Figs. 1 and 4). Affymetrix gene chips analysis revealed dynamic changes in hepatic gene expression (Supplementary Fig. S3), which were confirmed by IHC staining, RTD-PCR and Western blotting. Pathway analysis of differentially expressed genes suggested that the transcriptional regulators Sp1 and Ap1 are key regulators in the peretinoin inhibition of hepatic fibrosis and tumor development in Pdgf-c Tg mice (Supplementary Fig. S5).

We clearly showed that peretinoin inhibited PDGF signaling through the inhibition of PDGFRs (Figs. 2 and 3).
addition, we showed that PDGFR repressing by peretinoin inhibited primary stellate cell activation (Fig. 5). Interestingly, this inhibitory effect was more pronounced than the effects of 9cRA (Fig. 5B). Normal mouse and human hepatocytes neither express PDGF receptors (J.S. Campbell and N. Fausto, unpublished data), nor proliferate in response to treatment with PDGF ligands (7). However, peretinoin inhibited the expression of PDGF-Rs, collagens, and their downstream signaling molecules in cell lines of hepatoma (Huh-7, HepG2, and HLE), fibroblast (NIH3T3), endothelial cells (HUVEC), and stellate cells (Lx-2; Supplementary Fig. S6). Furthermore, Sp1 but not Ap1, might be involved in the repression of PDGFR in Huh-7 cells (Supplementary Fig. 6C). The overexpression of Sp1-activated PDGFR-α promoter activity, whereas siRNA knockdown of Sp1 repressed PDGFR-α promoter activity in Huh-7 cells (data not shown). Therefore, this seems to confirm that Sp1 is involved in the regulation of PDGFR, as reported previously (37, 38), although these findings should be further investigated in different cell lines. A recent report showed the involvement of transglutaminase 2, caspase3, and Sp1 in peretinoin signaling (35).

Peretinoin was shown to inhibit angiogenesis in the liver of Pdgf-c Tg mice in this study, as shown by the decreased expression of VEGFR1/2 and Tie 2 (Figs. 2 and 6 and Supplementary Fig. S1). Moreover, peretinoin inhibited the number of CD31⁺ and CD34⁺ endothelial cells (CEC) in the blood and liver (Fig. 6C and D), while also inhibiting the expression of EGFR, e-kit, PDGF-Rs, and VEGFR1/2 in Pdgf-c Tg mice (data not shown). We also showed that peretinoin inhibited the expression of multiple growth factors such as HGF, IGF, VEGF, PDGF, and HGF, which were upregulated from 3- to 10-fold in Pdgf-c Tg mice (Supplementary Fig. S3). These activities collectively might contribute to the antitumor effect of peretinoin in Pdgf-c Tg mice. The inhibition of both PDGFRs and VEGFR signaling by peretinoin was previously shown to have a significant effect on tumor growth (36), and we confirmed herein that peretinoin inhibited the expression of VEGFR2 in HUVECs (Supplementary Fig. S6; ref. 39). Finally, we showed that peretinoin inhibited canonical Wnt/β-catenin signaling by showing the decreased nuclear accumulation of β-catenin (Fig. 7). These data confirm the previous hypothesis of transrepression of the β-catenin promoter by 9cRA in vitro (40).

Although we showed that the PDGF signaling pathway is a target of peretinoin for preventing the development of hepatic fibrosis and tumors in mice, retinoid-inducing genes such as G0S2 (41), TGM2 (35), CEPP (42), ATP, TP53BP, metallothionein 1H (MT1H), MT2A, and hemopexin (HPX) were upregulated in peretinoin-treated mice (data not shown). These canonical retinoid pathways are likely to participate in preventing disease progression in conjunction with anti-PDGF effects.

The precise mechanism of peretinoin toxicity, in which 5% of mice treated with 0.06% peretinoin died after 24 weeks of treatment, is currently under investigation. These mice showed severe osteopenia and we speculate that the toxicity might be caused by retinoid-induced osteopenia, as observed in a hypervitaminosis A rat model (43). However, the toxicity of prolonged treatment with oral retinoids in humans remains controversial (44) and severe osteopenia has so far only been seen in a rodent model.

In summary, we show that peretinoin effectively inhibits hepatic fibrosis and HCC development in Pdgf-c Tg mice. Further studies are needed to elucidate the detailed molecular mechanisms of peretinoin action and the effect of peretinoin on PDGF-C in human HCC. The recently developed multi-kinase inhibitor Sorafenib (BAY 43-9006, Nexavar) was shown to improve the prognosis of patients with advanced HCC (45). Promisingly, a phase II/III trial of peretinoin showed it to be safe and well tolerated (46). Therefore, combinatorial therapy that incorporates the use of small molecule inhibitors with peretinoin may be beneficial to some patients. The application of peretinoin during pre- or early-fibrosis stage could be beneficial in preventing the progression of fibrosis and subsequent development of HCC in patients with chronic liver disease.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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