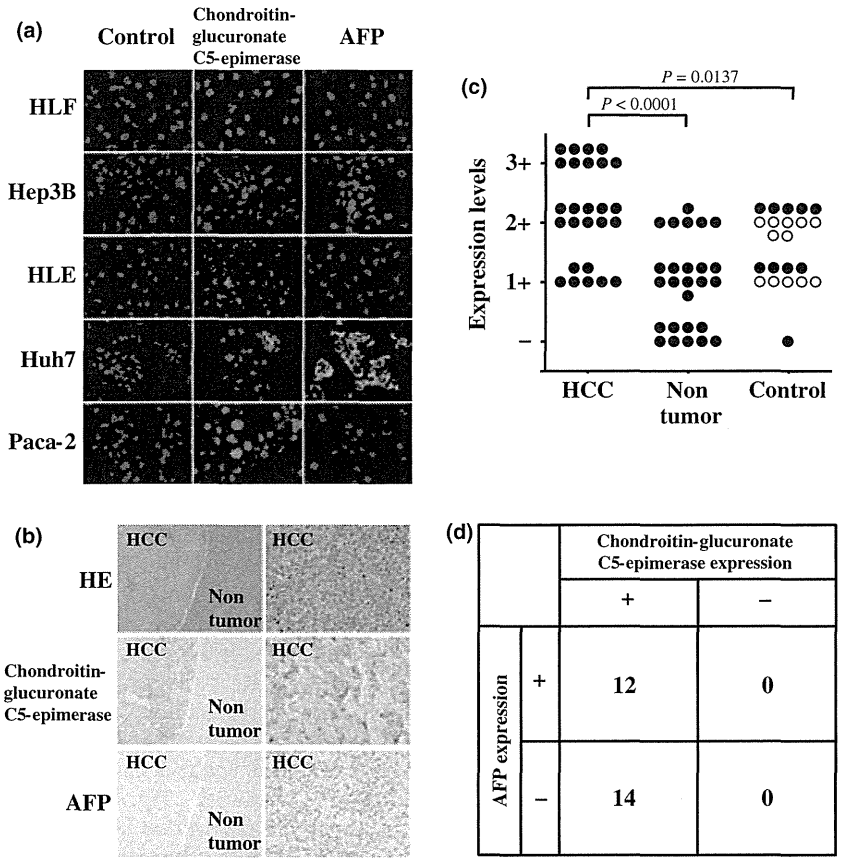

Fig. 1. Expression of chondroitin-glucuronate C5-epimerase. (a) immunofluorescence analysis for the expression of chondroitin-glucuronate C5-epimerase in hepatoma cell lines. Original magnification, ×400. (b) Immunohistochemical analysis for the expression of chondroitin-glucuronate C5-epimerase and AFP in sequential non-cancerous and HCC tissue sections. Original magnification, ×200 (left) and ×400 (right). (c) Analysis of chondroitin-glucuronate C5-epimerase expression levels among the three groups (HCC; tumour tissue in HCC patients, Non-tumour; non-tumour tissue in HCC patients, Control; liver tissue in disease control groups). Closed and open circles show the level of chondroitin-glucuronate C5-epimerase expression in the patients with cirrhosis and chronic hepatitis respectively. (d) The expression of chondroitin-glucuronate C5-epimerase was also compared with AFP expression in HCC tissues.

of the number of T cells that specifically reacted with the peptide in healthy donor-derived PBMCs as a significant response, 1 of 23 (4.3%) patients showed a significant response to each of the chondroitin-glucuronate C5-epimerase-derived peptides (Fig. 2a).

In the same analysis of HCC patients, 10.8, 16.2 and 27.0% of the patients showed significant responses to peptide 1, 2 and 3 respectively (Fig. 2b). A significant response specific to $CMVpp65_{328}$ was detected in 36.4%, 34.8% and 45.9% of healthy donors, disease control groups and HCC patients, respectively, with no significant difference among the three groups. On the other hand, no significant response to $HIVenv_{584}$ was observed in all groups.

To clarify the clinical characteristics of chondroitin-glucuronate C5-epimerase-specific T-cell responses in HCC patients, the clinical background was compared between patients who showed positive responses to chondroitin-glucuronate C5-epimerase-derived peptides and those who did not. The clinical features of both groups were not statistically different in terms of age, gender, serum AFP levels, differentiation of HCC, tumour multiplicity, vascular invasion, TNM factors and stages, histology of the non-tumour liver, liver function and the type of viral infection (Table 2). Chondroitin-glucuronate C5-epimerase-specific T cells had been generated even in the early stages of HCC.

Next, to examine the existence of chondroitin-glucuronate C5-epimerase-specific T cells among TILs, we performed a similar analysis in another seven patients from whom samples of both PBMCs and TILs could be obtained. In the assay using PBMCs and TILs, four of seven (57.1%) and five of seven (71.4%) patients, respectively, showed significant responses to chondroitin-glucuronate C5-epimerase-derived peptide (peptide 3) (Fig. 3a). A positive T-cell response in TILs was observed even in one patient without a positive T-cell response in PBMCs (patient 39).

Table 1. Characteristics of the patients studied

Clinical diagnosis	No. of patients	gender M/F	Age (yr) Mean ± SD	ALT (IU/L) Mean ± SD	AFP (ng/ml) Mean ± SD	Aetiology (B/C/Others)	Child-Pugh (A/B/C)	Diff. degree[a] (wel/mod /por/ND)	Tumour size[b] (large/small)	Tumour multiplicity (multiple/solitary)	Vascular Invasion (+/−)	TNM stage (I/II/IIIA/IIIB/ IIIC/IV)
Normal donors	11	8/3	35 ± 2	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chronic hepatitis	12	7/5	54 ± 11	104 ± 119	12 ± 4	0/12/0	12/0/0	ND	ND	ND	ND	ND
Liver cirrhosis	11	5/6	60 ± 11	83 ± 73	79 ± 140	1/7/3	6/5/0	ND	ND	ND	ND	ND
HCC	44	35/9	66 ± 8	67 ± 32	1629 ± 7874	8/34/2	28/14/2	11/17/3/13	29/15	25/19	12/32	13/17/5/ 1/2/6

[a]Histological degree of HCC; wel: well-differentiated, mod: moderately differentiated, por: poorly differentiated, ND: not determined.
[b]Tumour size was divided into either 'small' (≤2 cm) or 'large' (>2 cm).

Cytotoxic activity of chondroitin-glucuronate C5-epimerase-specific CTLs against hepatoma cell lines

Whether the chondroitin-glucuronate C5-epimerase-derived peptides used were capable of generating peptide-specific CTLs from PBMCs was investigated in 18 HCC patients. The CTLs specific to chondroitin-glucuronate C5-epimerase could be induced in 8 of 18 (44.4%) patients (Fig. 3b and c). They exhibited cytotoxicity against hepatoma cell lines with the HLA-A24 molecule and expression of chondroitin-glucuronate C5-epimerase, that correspond to HLF and HLE, but not against Hep3B and Huh7 cells without HLA-A24 (Fig. 3d).

Clinical safety of chondroitin-glucuronate C5-epimerase-derived peptide and its immunological effects

The clinical profiles of the 12 HCC patients with vaccination are shown in Table 3. The treatment was well-tolerated and there were no treatment-related serious adverse events. The most common adverse event was grade 1 injection-site reaction manifesting as pain, pruritus, skin induration and rubor. The worsening of hepatitis or liver function was not observed in any of the vaccinated patients.

In the analysis of ELISPOT assay using PBMCs of patients with vaccination, 4 patients demonstrated an immune response (Fig. 4a and Table 3). All of the patients that responded were immunized with 3.0 mg of peptide. None of the patients immunized with 0.03 or 0.3 mg of peptide showed an enhancement of peptide-specific immune response. The enhancement of immunological response to $HIVenv_{584}$ and $CMVpp65_{328}$ was not observed in any patients except patient A2.

To examine whether similar occurs for the immune response in HCC patients with only RFA, we analysed chondroitin-glucuronate C5-epimerase-derived peptide-specific T-cell responses in 12 HCC patients without vaccination, whose PBMCs were available for analysis at 2–4 weeks after RFA. In this analysis, we observed an increase of the frequency of chondroitin-glucuronate C5-epimerase-derived peptide-specific T cells in 2 of 12 patients (Fig. 4b). The frequency of the patients who showed an increase in the number of chondroitin-glucuronate C5-epimerase-derived peptide-specific T cells was higher in the patients with vaccination of 3 mg of peptide (66.7%) than in those without vaccination (16.7%).

Finally, we examined the HCC recurrence rate after RFA between the patients with and without the peptide-specific CTL response to examine the clinical effect of an increase of chondroitin-glucuronate C5-epimerase-derived peptide-specific CTLs after vaccination. In the analysis, the recurrence rate in the patients with an increase in the peptide-specific CTLs after vaccination (two of four patients, 50%) was lower than that in the patients without immune response (six of eight patients, 75%) at 300 days after RFA, although there was no sta-

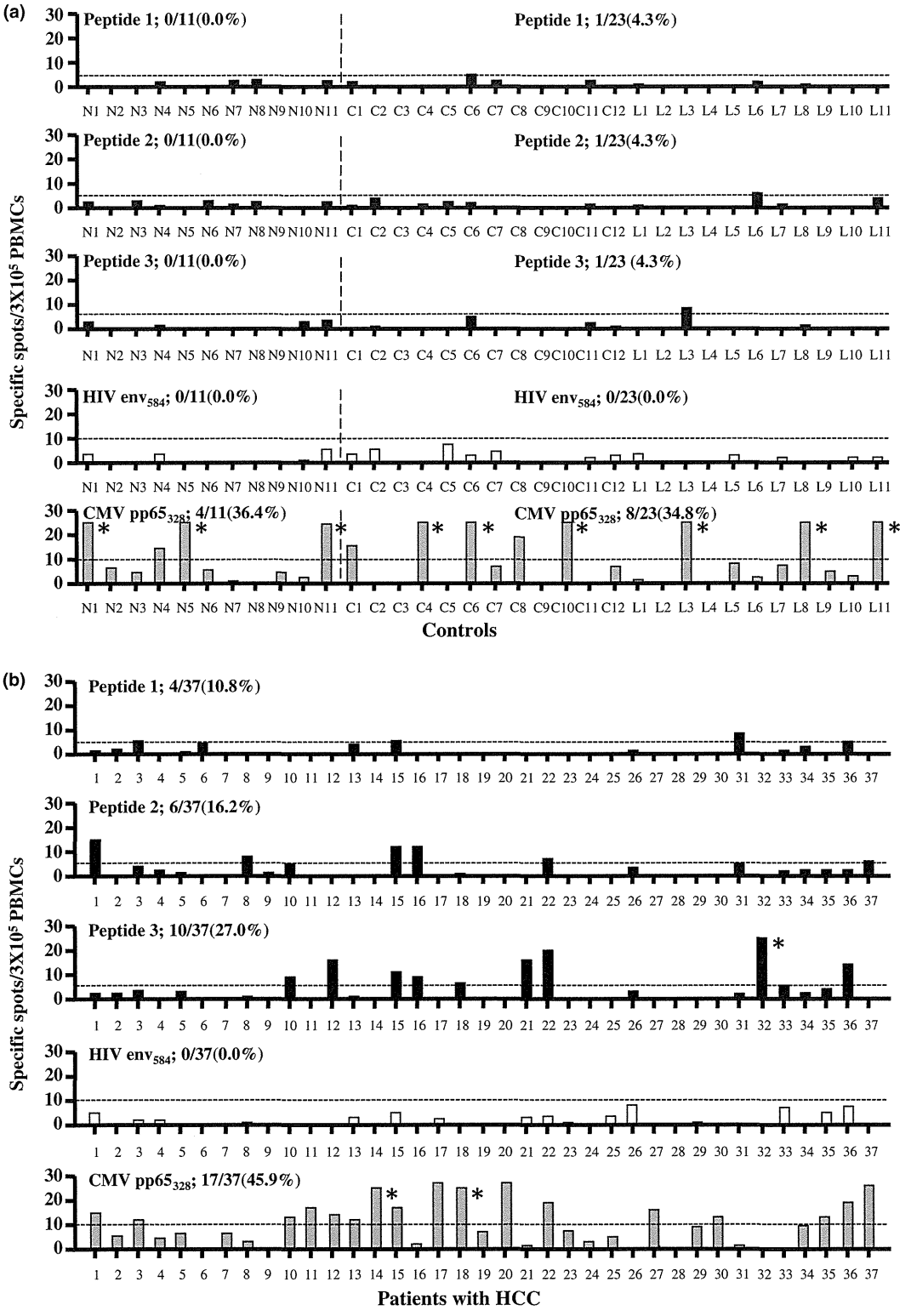

Fig. 2. Immune responses of chondroitin-glucuronate C5-epimerase-specific T cells. (a) IFN-γ ELISPOT assay of PBMCs to chondroitin-glucuronate C5-epimerase-derived peptides (peptides 1, 2 and 3: solid bars) or control peptides (peptides HIVenv$_{584}$ and CMVpp65$_{328}$: open and grey bars respectively) in normal donors and disease control groups. "N" denotes normal donors. "C" denotes the patients with chronic hepatitis. "L" denotes the patients with cirrhosis.% shows the ratio of the patients who showed positive responses. *denotes more than 30 specific spots. (b) IFN-γ ELISPOT assay in HCC patients. *denotes more than 30 specific spots.

Table 2. Univariate analysis of the effect of variables on the T-cell response against chondroitin-glucuronate C5-epimerase

	Patients with positive T-cell response	Patients without positive T-cell response	*P*-value[a]
No. of patients	15	22	
Age (years)[b]	64.6 ± 9.8	68.7 ± 5.9	NS
gender(M/F)	14/1	15/7	NS
AFP (ng/ml)	3569.7 ± 13070.0	580.7 ± 2394.2	NS
Diff. degree of HCC (well/moderate or poor/ND)[c]	3/7/5	8/6/8	NS
Tumour multiplicity (multiple/solitary)	10/5	13/9	NS
Vascular invasion (+/-)	5/10	6/16	NS
TNM factor			
(T1/T2–4)	4/11	8/14	NS
(N0/N1)	14/1	22/0	NS
(M0/M1)	13/2	20/2	NS
TNM stage (I/II–IV)	4/11	8/14	NS
Histology of non-tumour liver (LC/Chronic hepatitis)	12/3	20/2	NS
Liver function (Child A/B/C)	11/4/0	13/7/2	NS
Aetiology (HCV/HBV/Others)	11/3/1	20/1/1	NS
T-cell response against to CMV $pp65_{328}$ (+/-)	9/6	9/13	NS

[a]NS: not significant.
[b]Data are expressed as the mean ± SD.
[c]ND: not determined.

tistical significance owing to the small number of patients.

Discussion

Many tumour-associated antigens and their epitopes capable of inducing HLA-class I-restricted CTLs have been identified in various cancers. Some of the epitopes have been under investigation for the treatment of cancer, with major clinical responses in some trials (11, 20–22).

With regard to immunotherapy for HCC, AFP is considered a useful tumour-associated antigen and AFP-derived peptides have actually been used in clinical trials (5, 23–25). However, in general, the production of AFP depends on the size of the tumour, with AFP expressed in only 0–40% of HCCs less than 30 mm in size (26). Therefore, for immunotherapy for HCC in cases where AFP is not expressed in tumour tissue, it is necessary to identify other tumour-associated antigens.

In the present study, the expression of chondroitin-glucuronate C5-epimerase was observed in all of the HCC tissues examined and independent of differential degree, size, TNM stage and the expression of AFP in the tumour. These results suggest the advantage of this antigen as a target for immunotherapy of HCC.

On the other hand, the expression of this protein was also observed in non-cancerous tissue of HCC patients, although less frequently and at lower levels than in HCC tissue. Our results are consistent with the recent finding that chondroitin-glucuronate C5-epimerase is expressed in some normal tissues including liver tissue (6). Such results imply that immunotherapy targeting chondroitin-glucuronate C5-epimerase may have adverse effects on liver tissue expressing the protein. Therefore, we next examined the existence and specificity of chondroitin-glucuronate C5-epimerase-specific CTLs in HCC patients.

The presence of chondroitin-glucuronate C5-epimerase-recognizing CTLs has been reported as SART2-specific CTLs in lung, gastric and pancreatic cancer patients (7, 27, 28). However, to our knowledge, there has been no report of the presence of chondroitin-glucuronate C5-epimerase-specific CTLs in HCC patients except our recent study using only one SART2-derived peptide (10). In this study, we used three different HLA-A24 restricted peptides which were previously identified and derived from naturally processed squamous cell carcinoma antigen. The HLA-A24 allele is found in 60% of Japanese (29), and therefore, to use HLA-A24-restricted peptides has the advantage of analysing CTL responses to tumour-associated antigens in Japanese patients.

We showed that chondroitin-glucuronate C5-epimerase-specific CTLs could be generated by stimulating PBMCs with peptides, and the CTLs were cytotoxic to hepatoma cell lines. Chondroitin-glucuronate C5-epimerase-specific immune responses were observed frequently only in HCC patients and the frequency of CTLs was higher in HCC patients than control groups, indicating that the immune responses are specific to HCC. Furthermore, the CTLs were also detected among TILs, suggesting that they infiltrate the tumour. Based on these findings, we confirmed that chondroitin-glucuronate C5-epimerase-specific CTL precursors exist in HCC patients and the immune responses are specific for HCC.

In previous study, we reported that the frequency of TAA-derived peptide-specific CTLs in HCC patients was 0–92 cells/3 × 10^5 PBMCs and the frequency of the

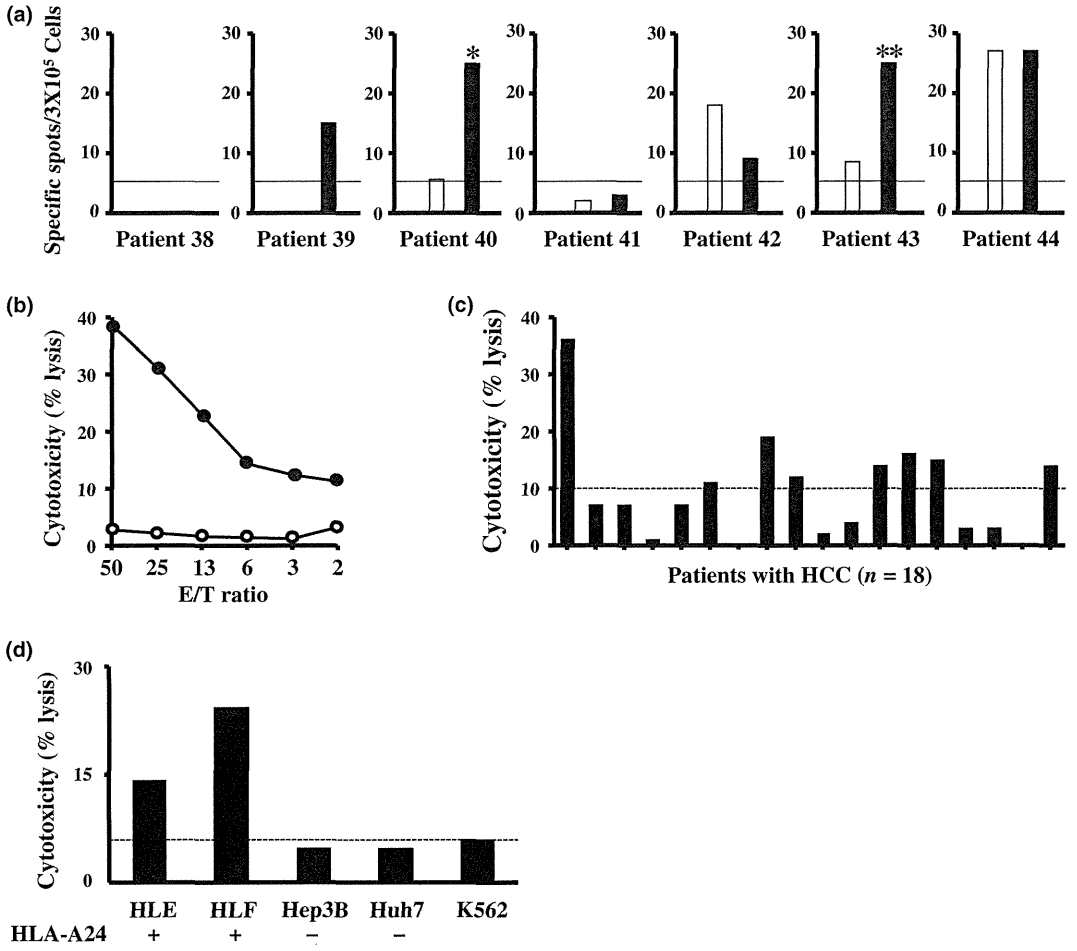

Fig. 3. Characteristics of chondroitin-glucuronate C5-epimerase-specific CTLs. (a) IFN-γ ELISPOT assay of PBMCs and TILs to one of the chondroitin-glucuronate C5-epimerase-derived peptide (peptide 3) in seven HCC patients. Open and solid bars show the frequency of chondroitin-glucuronate C5-epimerase-specific T cells in PBMCs and TILs respectively. *denotes 114 specific spots. **denotes 42 specific spots. (b) Representative results of the CTL assay. The closed and open circles show the cytotoxicity against C1R-A*2402 cells pulsed with and without a peptide respectively. (c) CTL assays (E/T ratio of 50:1) were performed in 18 HCC patients. Solid bars show the result for one patient. The results are shown as specific cytotoxic activity, which was calculated as follows: (cytotoxic activity in the presence of peptide) - (cytotoxic activity in the absence of peptide) and considered positive when higher than 10%. (d) Cytotoxicity of chondroitin-glucuronate C5-epimerase-specific T-cell lines derived with peptides was also measured against hepatoma cell lines. The cytotoxicity was considered positive when it was higher than that against K562 which shows non-specific lysis (E/T ratio of 50:1).

patients who showed immune responses to each peptide was 0–19% (10). In the present study, the frequency of chondroitin-glucuronate C5-epimerase-derived peptide-specific CTLs in HCC patients was 0–30 cells/ 3×10^5 PBMCs and the frequency of the patients who showed immune responses to the peptides was 11–27%. These results show that the frequencies of chondroitin-glucuronate C5-epimerase-specific CTLs in PBMCs and the patients with CTLs responsive to the TAA are very similar to those of previously identified immunogenic TAA-derived epitopes and suggest that the antigen and its CTL epitope are immunogenic. In addition, the CTLs were generated even in the early stages of HCC. These results suggest the advantages of using chondroitin-glucuronate C5-epimerase-derived peptides as a vaccine for immunotherapy of HCC.

For the next step to investigate the usefulness of chondroitin-glucuronate C5-epimerase as an immunotherapeutic target in HCC, we examined the safety and efficacy of chondroitin-glucuronate C5-epimerase-derived peptide as a cancer vaccine. In previous studies using chondroitin-glucuronate C5-epimerase-derived peptides for several cancers, they were reported to be safe. However, most patients with HCC have chronic liver disease. Therefore, safety of the peptide vaccine should be confirmed in the patients with chronic hepatitis or cirrhosis. The present vaccination study included nine patients with chronic liver diseases (four chronic hepatitis and five cirrhotic patients) confirmed by histological examination and there was no severe adverse event in all patients vaccinated. The induction of chondroitin-glucuronate C5-epimerase-specific CTLs

Table 3. Patient characteristics

Patient	Peptide Dose (mg)	Age	gender	Aetiology	Stage of HCC	ALT (IU/L)	AFP (ng/ml)	Child-Pugh (A/B/C)	Histology of liver	Treatment	Immune response	Toxicity (grade)
A1	0.03	73	F	HCV	I	26	12	A	F4A2	RFA	–	Pa(1)
A2	0.03	78	F	HCV	I	45	10	B	F4A2	RFA	–	P(1)
A3	0.03	59	M	NBNC	II	30	10	A	ND	RFA	–	None
B1	0.3	79	M	HCV	I	40	61	A	F3A1	RFA	–	R(1), S(1)
B2	0.3	72	M	NBNC	II	24	66	A	ND	RFA	–	R(1), S(1), P(1), H(1)
B3	0.3	78	M	HCV	II	45	10	A	F3A2	RFA	–	P(1)
C1	3.0	67	M	HCV	I	111	49	A	F3A1	RFA	+	P(1), S(1)
C2	3.0	73	M	NBNC	I	30	5	A	ND	RFA	–	None
C3	3.0	78	F	HCV	I	23	24	A	F4A2	RFA	+	P(1)
C4	3.0	75	M	HBV	I	21	15	A	F3A1	RFA	+	R(1), P(1)
C5	3.0	49	M	HBV	I	18	14	A	F4A1	RFA	+	None
C6	3.0	69	F	HBV	II	42	84	A	F4A2	RFA	–	Pa(1)

H, headache; Pa, pain; P, pruritus; R, rubor; S, skin induration.

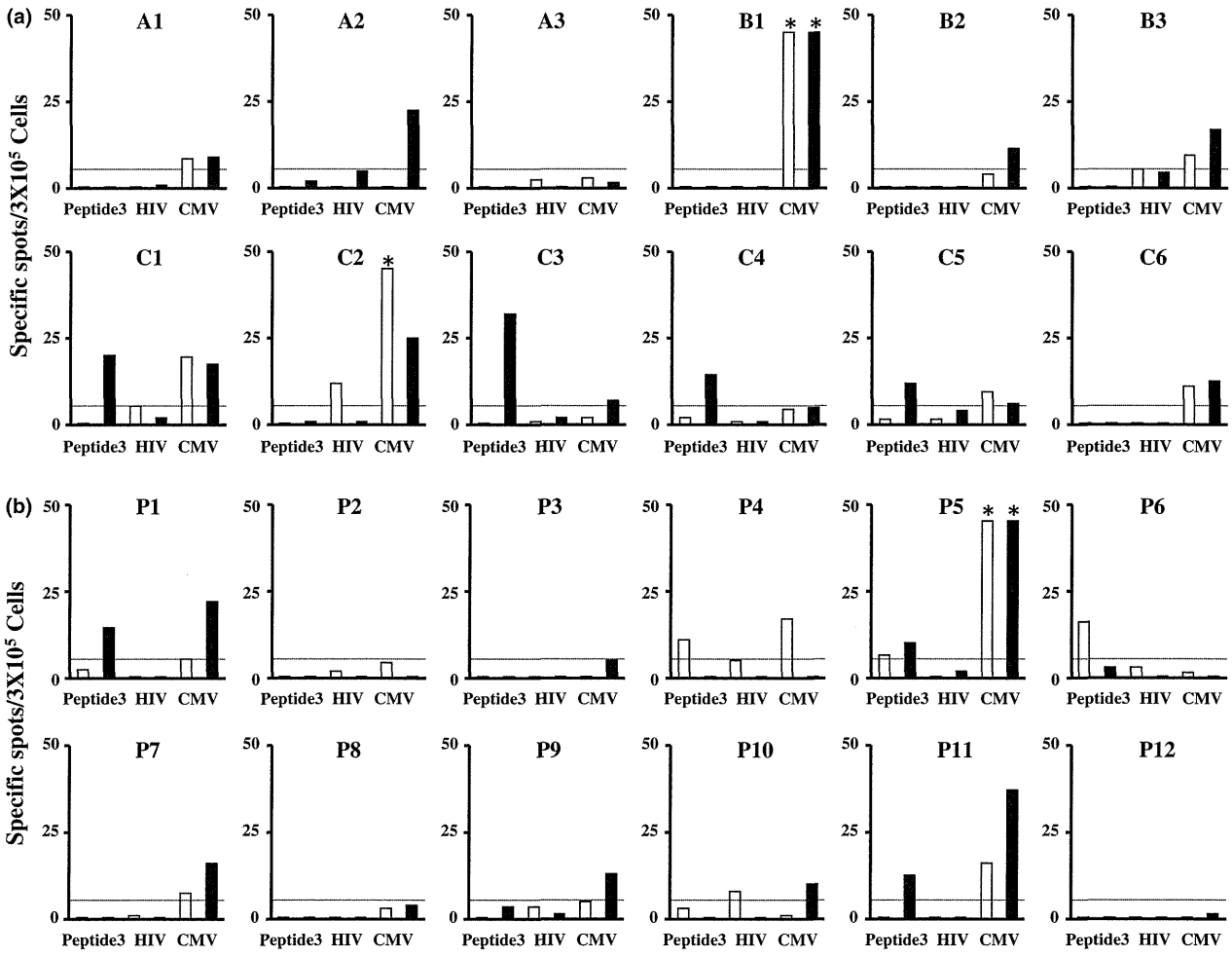

Fig. 4. IFN-γ ELISPOT assays of PBMCs to chondroitin-glucuronate C5-epimerase-derived peptide (peptide 3) or control peptides (peptides $HIVenv_{584}$ and $CMVpp65_{328}$) in HCC patients with RFA. (a) The assays were performed in the patients with peptide 3 vaccination. White and black bars show the T-cell responses before and after vaccination respectively. (b) The assays were also performed in the patients without vaccination. White and black bars show the T-cell responses before and after RFA respectively. *denotes more than 50 specific spots.

was observed in four of six (66.7%) patients vaccinated with 3 mg of peptide, which is similar to the frequency of responded patients reported in other peptide vaccination studies (11, 20).

Apart from induction of CTLs, the efficacy of chondroitin-glucuronate C5-epimerase-derived peptides as a vaccine for advanced HCC is still unclear. In previous vaccine studies for advanced HCC, AFP, hTERT and glypican-3 have been targeted as tumour-associated antigens for the treatment (25, 30–32). In these studies, peptide-specific CTLs were reported to be induced in 10–80% of vaccinated patients. However, in spite of the induction of peptide-specific CTLs, it has been reported that the anti-tumour effect was very limited. Recent studies have shown that the frequency of myeloid-derived suppressor cells (MDSCs) and regulatory T cells (Tregs) is increased in HCC patients and the cells inhibit the function of T cells (33, 34). Therefore, controlling their function might be important to develop more effective vaccination for advanced HCC.

In contrast, other recent studies using chondroitin-glucuronate C5-epimerase-derived peptides for other advanced cancers have shown the induction of cellular immune responses and clinical responses for certain patients (9, 11). In the analysis of the prognosis of patients with RFA and chondroitin-glucuronate C5-epimerase-derived peptide vaccination in the present study, the recurrence rate in the patients with an increase in the peptide-specific CTLs after vaccination was lower than that in the patients without immune response. Although further studies are necessary to evaluate the efficacy of chondroitin-glucuronate C5-epimerase-derived peptides for HCC, the results of our study suggest that chondroitin-glucuronate C5-epimerase is a potential candidate for a target of HCC immunotherapy.

In conclusion, chondroitin-glucuronate C5-epimerase is a potential candidate for a tumour antigen with immunogenicity, and peptides derived from the protein would be useful for immunotherapy in cases of HCC.

Acknowledgements

The authors thank Maki Kawamura and Nami Nishiyama for technical assistance.

Financial support: This study was supported by research grants from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

Conflict of interest: The authors who have taken part in this study declared that they do not have anything to disclose regarding funding or conflict of interest with respect to this manuscript.

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Cancer Research

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.

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Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org/).

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doi: 10.1158/0008-5472.CAN-12-0028

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 a 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% CO_2 at 37°C. 1 to 5×10^4 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% CO_2 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-Phycoerythrin (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 (BIOREVO 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 CelLytic MT cell lysis reagent (Sigma-Aldrich) containing Complete Mini EDTA-free Protease Inhibitor cocktail tablets (Roche). 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), cyclin D1 (1:400 dilution), and lamin A/C (1:1,000 dilution; all Cell Signaling Technology); α-SMA (1:200 dilution; DAKO); 4-HNE (1:200 dilution; NOF); and GAPDH (1:1,000 dilution) and Myc (1:1,000 dilution; both Santa Cruz).

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*

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)1, 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

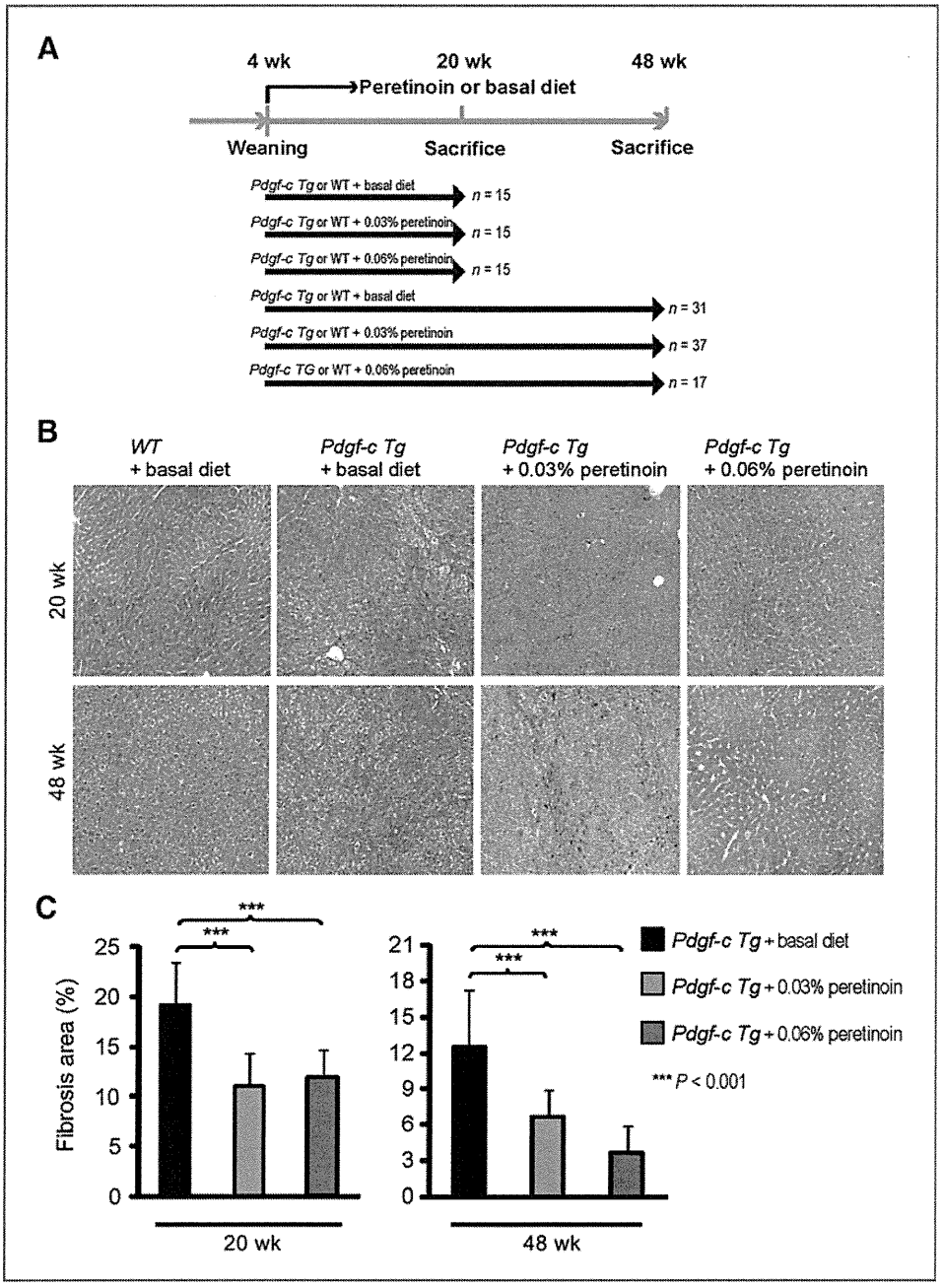

Figure 1. A, feeding schedule of *Pdgf-c Tg* and WT mice. After weaning, male mice were randomly divided into 3 groups: (i) *Pdgf-c Tg* or WT mice receiving basal diet, (ii) *Pdgf-c Tg* or WT mice receiving 0.03% peretinoin-containing diet, and (iii) *Pdgf-c Tg* or WT mice receiving 0.06% peretinoin-containing diet. B, Azan staining of WT or *Pdgf-c Tg* mouse livers fed with different diets at 20 weeks and 48 weeks. C, densitometric analysis of *Pdgf-c Tg* mouse liver fibrotic areas at 20 weeks ($n = 15$) and 48 weeks ($n = 15$).

48. 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).

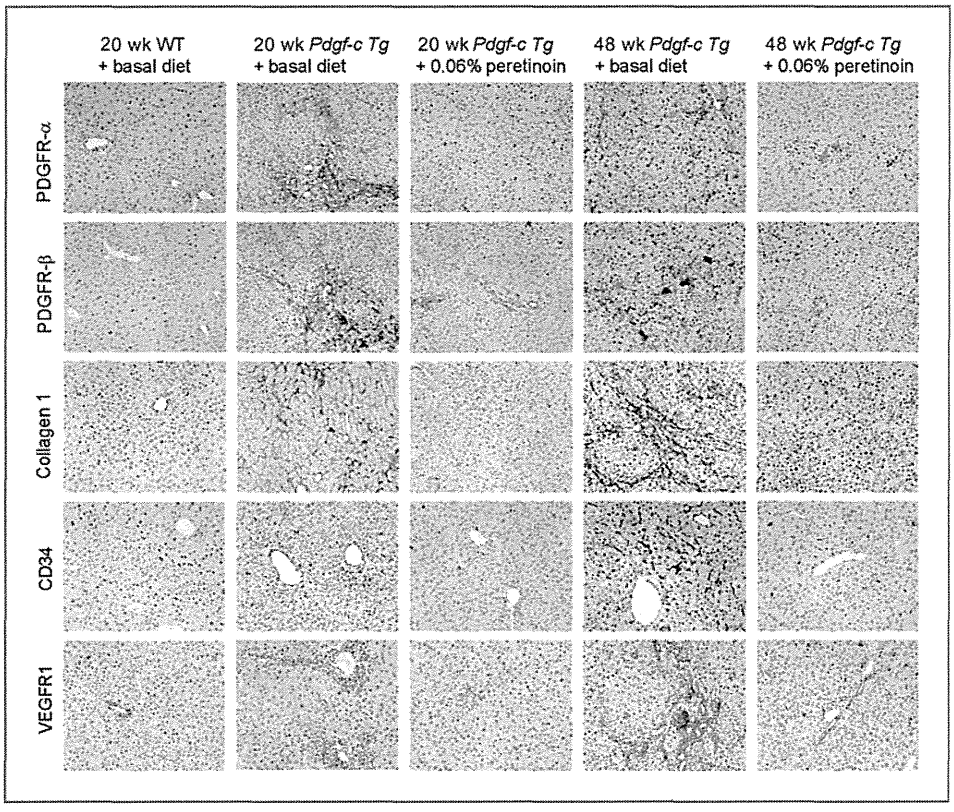

Figure 2. IHC staining of PDGFR-α, PDGFR-β, collagen 1, CD34, and VEGFR1 expression in *Pdgf-c Tg* or WT mouse livers fed a basal diet or 0.06% peretinoin.

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 TGFβR), 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-α, PDGFR-β, alpha smooth muscle actin (α-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 (NIH3T3), HUVECs, and Lx-2 (ref. 22; Supplementary Fig. S6A). Experimental conditions were optimized so that more than 90% of cells were variable at 20 μmol/L peretinoin, as determined by an MTS cell proliferation assay (data not shown). Peretinoin dose-dependently inhibited the expression of PDGFR-α and PDGFR-β in Huh-7, HepG2, HLE, NIH3T3, HUVEC, and Lx-2 cells, whereas no obvious expression of PDGFR-α 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-α, PDGFR-β, 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-α, 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

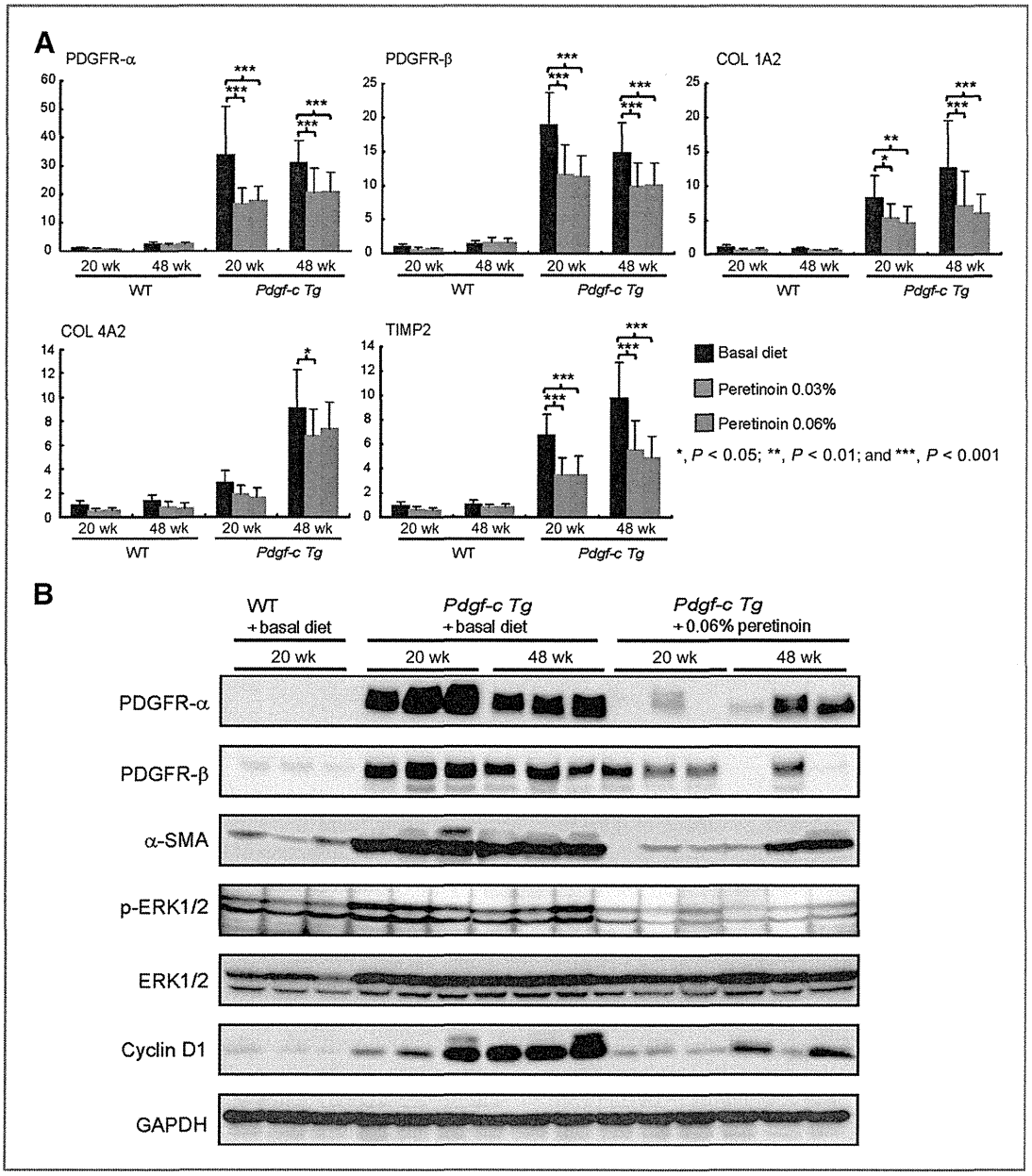

Figure 3. A, RTD-PCR analysis of PDGFR-α, PDGFR-β, collagen (COL) 1a2, collagen 4 a2, and TIMP2 expression in *Pdgf-c Tg* ($n = 5$) or WT mouse livers ($n = 15$). B, Western blotting of PDGFR-α, PDGFR-β, α-SMA, p-ERK, ERK, cyclin D1, and GAPDH expression in PDGF-C Tg or WT mouse livers fed a basal diet or 0.06% peretinoin at 20 or 48 weeks ($n = 3$).

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 $CD31^+/CD34^+$ CEC population was significantly upregulated in *Pdgf-c Tg* mice at week 48 but significantly repressed by peretinoin (Fig. 6C and D). Thus, peretinoin

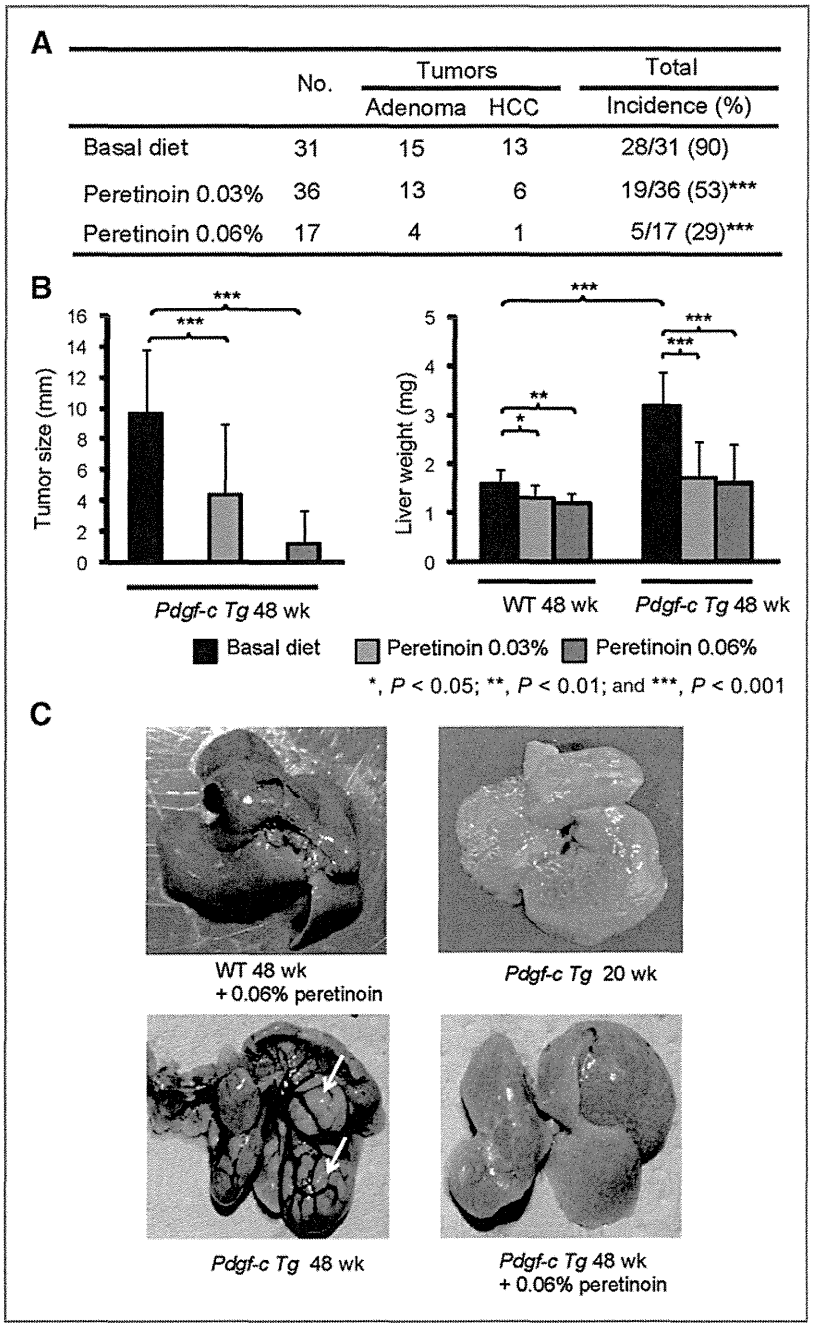

Figure 4. A, incidence of hepatic tumors (adenoma or HCC) in *Pdgf-c Tg* mouse livers fed with different diets. B, tumor sizes and liver weights of *Pdgf-c Tg* and WT mice fed with basal diet ($n = 31$ for *Pdgf-c* Tg, $n = 15$ for WT mice) or 0.03% ($n = 36$ for *Pdgf-c* Tg, $n = 15$ for WT mice) and 0.06% ($n = 17$ for *Pdgf-c* Tg, $n = 15$ for WT mice) peretinoin at 48 weeks. C, macroscopic findings of *Pdgf-c Tg* or WT mouse livers. No obvious change was observed in the liver of WT mice fed with 0.06% peretinoin for 48 weeks (top left). Fibrosis and steatosis were observed in the liver of *Pdgf-c Tg* mice fed a basal diet for 20 weeks (top right). Multiple tumors developed (white arrows) in the liver of *Pdgf-c Tg* mice fed a basal diet for 48 weeks (bottom left). Suppression of tumor development in the liver of *Pdgf-c Tg* mice fed a 0.06% peretinoin diet for 48 weeks (bottom right).

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

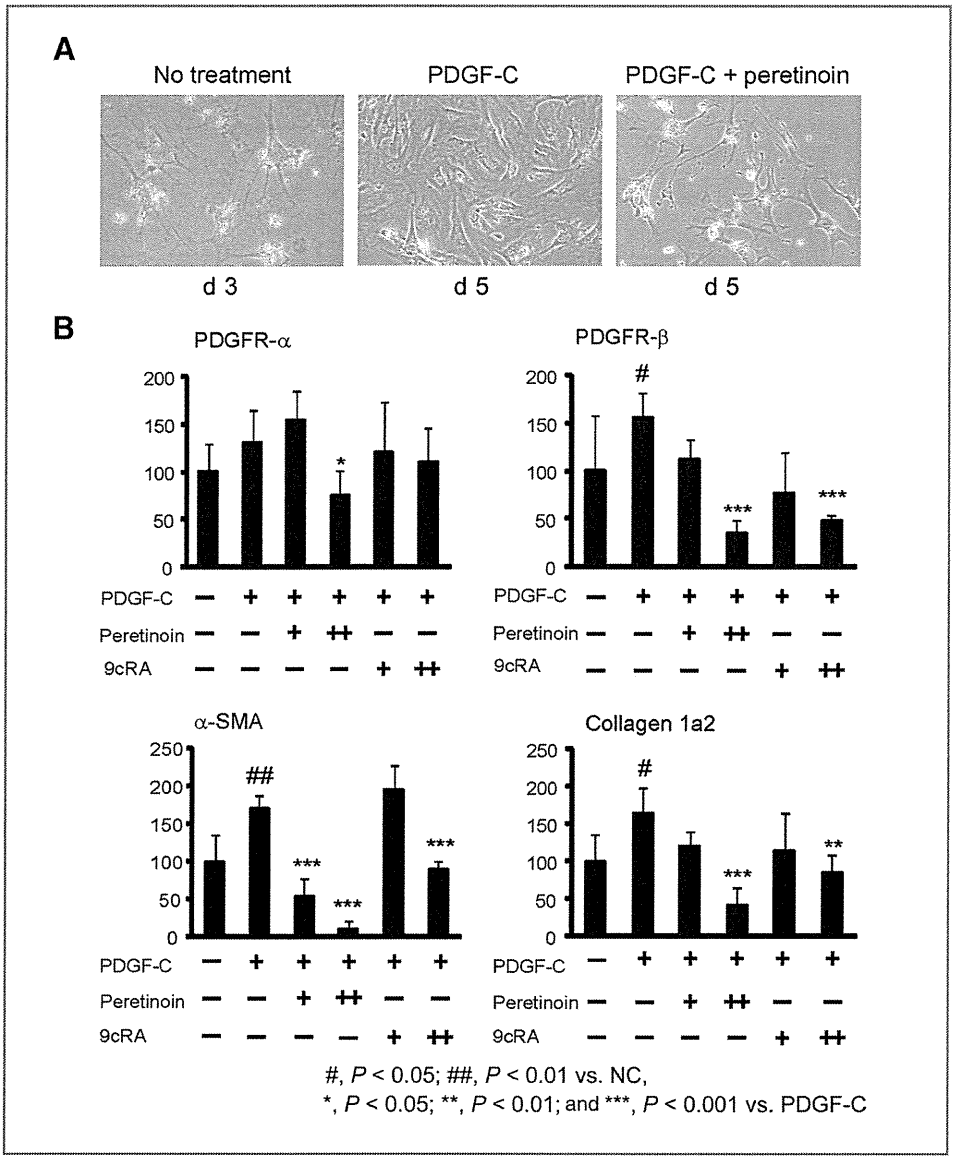

Figure 5. A, microscopic view of freshly isolated primary mouse HSCs after PDGF-C transformation into myofibroblasts (left). Peretinoin inhibited the transformation of HSCs by PDGF-C. B, RTD-PCR analysis of PDGFR-α, PDGFR-β, α-SMA, and collagen 1a2 expression in HSCs treated with or without PDGF-C, peretinoin, and 9cRA ($n = 4$). PDGF-C (+), 80 ng/mL; peretinoin (+), 5 μmol/L; (++), 10 μmol/L; 9cRA (+), 5 μmol/L; (++), 10 μmol/L. NC, no control.

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

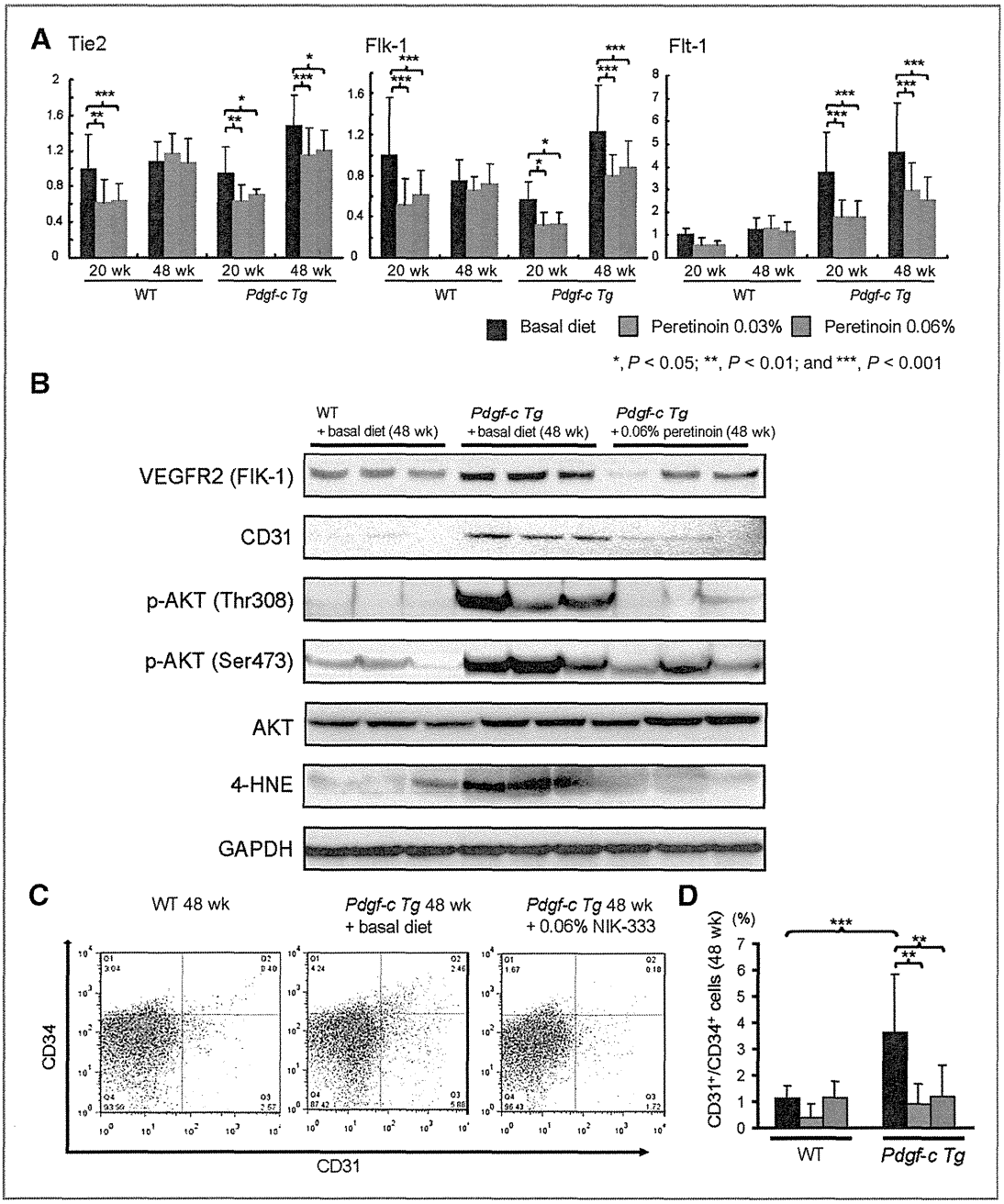

Figure 6. A, RTD-PCR analysis of Tie2, Flk-1, and Flt-1 expression in the liver of *Pdgf-c Tg* and WT mice fed with different diets ($n = 15$). B, Western blotting of Flk-1, CD31, p-AKT (Thr 308, Ser473), AKT, 4-HNE, and GAPDH expression in the liver of *Pdgf-c Tg* or WT mice fed a basal diet or 0.06% peretinoin at 48 weeks ($n = 3$). C, fluorescence-activated cell-sorting analysis of CD31- and CD34-positive CEC in blood of *Pdgf-c Tg* or WT mice fed a basal diet or 0.06% peretinoin at 48 weeks. D, frequency of CD31- and CD34-positive CEC in blood of *Pdgf-c Tg* or WT mice fed a basal diet or 0.06% peretinoin at 48 weeks ($n = 10$).

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

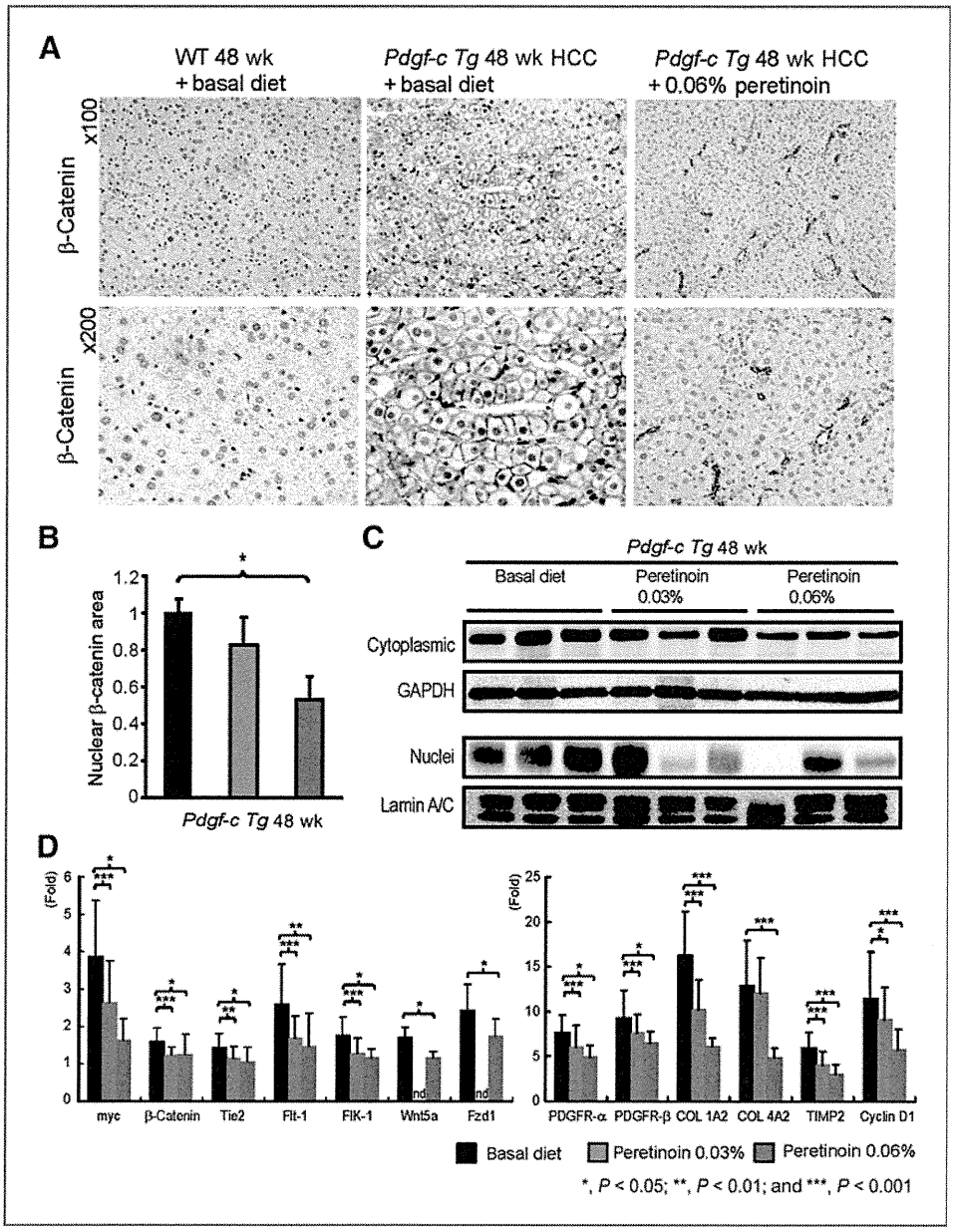

Figure 7. A, IHC staining of β-catenin expression in HCC tissues of *Pdgf-c Tg* mice fed a basal diet or 0.06% peretinoin at 48 weeks. B, densitometric analysis of β-catenin expression in the liver of *Pdgf-c Tg* mice fed with different diets ($n = 15$ for basal diet, $n = 15$ for 0.03% peretinoin, $n = 5$ for 0.06% peretinoin). C, Western blotting of β-catenin expression in cytoplasmic and nuclear fractions of *Pdgf-c Tg* mouse livers fed with different diets. GAPDH was used to standardize cytoplasmic protein and lamin A/C to standardize nuclear protein ($n = 3$). D, RTD-PCR analysis of myc, β-catenin, Tie2, Flt-1, Flk-1, Wnt5a, Fzd1, PDGFR-α, PDGFR-β, collagen (COL) 1a2, collagen 4a2, TIMP2, and cyclin D1 expression in HCC tissues of *Pdgf-c Tg* mice fed with different diets ($n = 15$ for basal diet, $n = 15$ for 0.03% peretinoin, $n = 5$ for 0.06% peretinoin). Relative fold expressions compared with WT mice are shown.

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 tumorigenic 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). In

addition, we showed that PDGFR repression 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 PDGFRs, 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-α 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, c-kit, PDGFRs, 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 HDGF, 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), CEBPA (42), ATF, 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 multikinase 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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Writing, review, and/or revision of the manuscript: H. OkadaM. Honda, J.S. Campbell, N. Fausto, S. Kaneko
Study supervision: J.S. Campbell, S. Kaneko
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Acknowledgments

The authors thank Dr. Scott Friedman, Mount Sinai School of Medicine (New York, NY), for providing Lx-2 cell lines and Nami Nishiyama and Masayo Baba for their excellent technical assistance.

Grant Support

This work was funded by NIH grants CA-23226, CA-174131, and CA-127228 (J.S. Campbell and N. Fausto). This work was also supported in part by a grant-in-aid from the Ministry of Health, Labour and Welfare, and KOWA Co., Ltd., Tokyo, Japan (M. Honda and colleagues).

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Received January 9, 2012; revised April 27, 2012; accepted May 18, 2012; published OnlineFirst May 31, 2012.

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