Pirfenidone Inhibits Pancreatic Cancer Desmoplasia by Regulating Stellate Cells

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Abstract

Pancreatic stellate cells (PSC), which are implicated in desmoplasia in pancreatic cancer, enhance the malignancy of cancer cells and confer resistance to established treatments. We investigated whether the antifibrotic agent pirfenidone can suppress desmoplasia and exert antitumor effects against pancreatic cancer. Primary PSCs were established from pancreatic cancer tissue obtained during surgery. In vitro, pirfenidone inhibited the proliferation, invasiveness, and migration of PSCs in a dose-dependent manner. Although supernatants of untreated PSCs increased the proliferation, invasiveness, and migration of pancreatic cancer cells (PCC), supernatants of pirfenidone-treated PSCs decreased these effects. Exposure to PCC supernatant increased the production of platelet-derived growth factor-A, hepatic growth factor, collagen type I, fibronectin, and periostin in PSCs, which was significantly reduced by pirfenidone. Mice were subcutaneously implanted with PCCs (SUIT-2 cells) and PSCs into the right flank and PCCs alone into the left flank. Oral administration of pirfenidone to these mice significantly reduced tumor growth of co-implanted PCCs and PSCs, but not of PCCs alone. Pirfenidone also decreased the proliferation of PSCs and the deposition of collagen type I and periostin in tumors. In mice with orthotopic tumors consisting of PCCs co-implanted with PSCs, pirfenidone suppressed tumor growth, reduced the number of peritoneal disseminated nodules, and reduced the incidence of liver metastasis. Pirfenidone in combination with gemcitabine more effectively suppressed orthotopic tumor growth compared with pirfenidone or gemcitabine alone. In conclusion, our findings indicate that pirfenidone is a promising antitumor agent for pancreatic cancer, owing to its suppression of desmoplasia through regulating PSCs. Cancer Res; 73(7); 2345–56. ©2013 AACR.

Introduction

Pancreatic cancer is characterized by excessive desmoplasia, which drives the aggressive behaviors of pancreatic cancer and resistance to traditional therapies through tumor-stromal interactions (1). Pancreatic stellate cells (PSC) have been identified in the interlobular areas and in peri-acinar lesions of the pancreas and are responsible for generating extensive fibrosis in pancreatic diseases (2, 3). PSCs are activated by various stimuli and transform from quiescent cells to myofibroblast-like cells expressing α-smooth muscle actin (SMA; ref. 4). In pancreatic cancer, PSCs are activated by tumor–stromal interactions, including by direct contact with pancreatic cancer cells (PCC) and paracrine growth factors secreted from PCCs including TGF-β1, platelet-derived growth factor (PDGF), basic fibroblast growth factor (bFGF), and VEGF (5–8). Activated PSCs also secrete various growth factors, including PDGF, bFGF, TGF-β1, and connective tissue growth factor (CTGF), to stimulate PCCs via paracrine pathways and also activate PSCs via autocrine pathways. Activated PSCs can also produce abundant extracellular matrix (ECM) and generate preferable microenvironments for PCCs. In vivo studies revealed that PCCs co-implanted with PSCs showed significant augmentation of tumor growth and very excessive desmoplasia (8–10). Excessive ECM deposition around tumor cells was reported to inhibit the distribution and penetration of anti-cancer drugs by decreasing tumor vascularity and constructing physical barriers (11, 12). These data suggest that desmoplasia consisting of PSCs and ECM provides a significant contribution to the malignant behaviors of cancer cells and resistance to established therapies, particularly for pancreatic cancer. Therefore, new strategies targeting desmoplasia are needed to improve the treatment paradigm of pancreatic cancer.

Pirfenidone [5-methyl-1-[2-[1H]-pyridone; Shionogi & Co. Ltd.; MARNAC Inc.] is a pyridone compound with therapeutic potential for idiopathic pulmonary fibrosis (IPF). Some double-blind, placebo-controlled phase II and III studies showed that pirfenidone has clinically meaningful effects and a favorable

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Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org).
safety profile in patients with IPF (13, 14). IPF is a chronic, progressive, and often fatal inflammatory lung disease that results in the proliferation of fibroblasts and deposition of ECM in the interstitium and alveolar spaces of lung (15). In animal models of lung fibrosis, pirfenidone inhibited fibroblasts and downregulated TGF-β, PDGF, and collagen synthesis (16–18). In liver fibrosis models, pirfenidone suppressed the proliferation of hepatic stellate cells, TGF-β mRNA expression, and the production of collagen type I (19, 20). These reports suggest that pirfenidone exerts antifibrotic effects by inhibiting fibroblasts and the production of TGF-β, PDGF, and collagen type I. To date, however, no studies have analyzed the effects of pirfenidone on PSCs derived from pancreatic cancer tissues. Therefore, the aim of this study was to evaluate whether pirfenidone could suppress desmoplasy in pancreatic cancer. We assessed the effects of pirfenidone on human PSCs and tumor–stromal interactions between PCCs and PSCs. We also investigated the effects of pirfenidone on pancreatic cancer xenografts co-implanted with PCCs and PSCs.

Materials and Methods

Cell isolation and culture conditions

We established human PSCs from pancreatic cancer surgical specimens using the outgrowth method described by Bachem and colleagues (3, 6), and cells were maintained as previously described (21). We confirmed that the PSCs exhibited a fibroblast-like morphology and were immunohistochemically positive for α-SMA and glial fibrillary acidic protein (GFAP), markers of PSCs, and were negative for cytokeratin, an epithelial cell marker (Supplementary Fig. S1). All of the established PSCs were used between passages 3 and 8. The use of pancreatic cancer surgical specimens was approved by the Ethics Committee of Kyushu University (Fukuoka, Japan) and was conducted according to the Ethical Guidelines for Human Genome/Gene Research enacted by the Japanese Government and the Helsinki Declaration. We also used 2 human pancreatic cell lines in this study: SUIT-2 and MIA PaCa-2 cells [Japan Health Science Research Resources Bank (JCRB), Osaka, Japan]. Both cell lines were propagated and frozen immediately after arrival. The cells revived from the frozen stock were used within less than 3 months. Cell lines were regularly authenticated and matched and short tandem repeat DNA profiles of the original cell lines by JCRB. The cells were maintained as previously described (21).

Pirfenidone and gemcitabine preparation and treatment

For in vitro studies, pirfenidone was purchased from Sigma-Aldrich. The powder was dissolved in sterile water at 60°C to a concentration of 10 mg/mL and frozen at −20°C until use. For in vivo studies, we purchased Pirespa tablets from Shionogi & Co. and gemcitabine from Eli Lilly & Company. The tablets were crushed using a pestle and mortar, and dissolved in sterile water to a pirfenidone concentration of 200 mg/mL. Pirfenidone was orally administered to nude mice (BALB/c nu/nu; Kyudo Co.) using a flexible gastric tube (KN-349, Natsume Sisakuyo Co, Ltd.) at a dose of 500 mg/kg. Gemcitabine was dissolved in PBS and intravenously injected into nude mice at a dose of 40 mg/kg.

Production of conditioned media of PCCs and PSCs

We produced conditioned media of PSCs and PCCs using serum-free Dulbecco’s Modified Eagle’s Media (DMEM) to exclude the effects of growth factors present in serum for the following experiments. Confluent (70%) SUIT-2 cells (SUIT-2-SN) and 100% confluent PSCs (PSC-SN) were cultured in serum-free DMEM for 24 or 48 hours, respectively. In experiments designed to analyze the effects of pirfenidone on PSCs, 100% confluent PSCs were cultured in serum-free DMEM containing 0.3 mg/mL pirfenidone for 48 hours (pirfenidone-treated PSC-SN). The resulting conditioned media were used to stimulate PCCs and PSCs. Proteins secreted into the supernatant were also examined. The conditioned media were centrifuged for 10 minutes at 1,000 rpm after collection and stored at −80°C until use.

Cell proliferation assay

Cell proliferation was evaluated by measuring the fluorescence intensity of propidium iodide (PI), as previously described (22). PSCs and PCCs were seeded in 24-well tissue culture plates (Becton Dickinson Labware) at a density of 1 × 10^4 or 2 × 10^4 cells/well, respectively. The cells were then cultured in DMEM containing 10% FBS for 24 hours. After confirmation of cellular adhesion to the plates, the medium was replaced with fresh DMEM containing 10% FBS plus pirfenidone at concentrations of 0, 0.1, 0.3, 0.5, or 1.0 mg/mL. To analyze cell proliferation following stimulation with conditioned medium, the medium was replaced with SUIT-2-SN, PSC-SN, or pirfenidone-treated PSC-SN containing 1% FBS plus 0 or 0.3 mg/mL pirfenidone. Cell proliferation was evaluated after culture for 72 hours using PI assays. A separate well containing the same medium and the same concentration of pirfenidone was used to provide a baseline PI signal as a control. The difference in intensity between each sample well and the control well was calculated.

Matrigel invasion and migration assays

Cell invasion was measured by counting the number of cells that invaded through Matrigel-coated Transwell chambers with 8-μm pores (BD Biosciences). The Transwell inserts were coated with 20 μg/well Matrigel (BD Biosciences). PSCs (3 × 10^4 cells) and PCCs (5 × 10^4 cells) were suspended in 250 μL of DMEM containing 10% FBS plus pirfenidone at concentrations of 0, 0.1, or 0.3 mg/mL and were placed in the upper chamber. The upper chamber was then placed in a 24-well culture dish containing 750 μL of the same medium with the same concentration of pirfenidone as used in the upper chamber. The migration of PSCs and PCCs was assessed using uncoated Transwell inserts. Separate batches of cells were cultured with SUIT-2-SN, PSC-SN, or pirfenidone-treated PSC-SN containing 2% FBS plus 0 or 0.3 mg/mL pirfenidone to assess the effects of PSC and PCC supernatant stimulation on migration and invasion. After incubation for 48 hours for invasion or 24 hours for migration, the invaded and migrated cells were fixed with 70% ethanol, stained with hematoxylin and eosin (H&E), and counted in 5 random fields at a magnification of ×100 under a light microscope. The results are expressed as the mean number of invaded
cells per field. Each experiment was carried out in triplicate wells and repeated 3 times.

**Quantitative real-time reverse transcription-PCR**

Quantitative real-time reverse transcription (qRT)-PCR was carried out as previously described (23). We designed specific primers for α-SMA, peristin, FGF-2, and 18S rRNA using Primer 3 software (http://primer3.sourceforge.net/). The primers used for collagen type I, fibronectin, TGF-β1, PDGF-A, PDGF-B, CTGF, hepatocyte growth factor (HGF), VEGF, and 18S rRNA were purchased from Takara Bio Inc. The primer sequences are listed in Supplementary Table S1.

**Western blotting analysis**

Protein was extracted from PSCs using PRO-PREP (iNtRON biotechnology) according to the manufacturer’s instructions. The supernatants were concentrated using an Amicon Ultra-10 filter unit (Millipore) at 4,000 rpm for 60 minutes, and Halt Protease and Phosphatase Inhibitor Single-Use Cocktail (Thermo Scientific) was added to each sample. The supernatants were stored at −80°C until use. Cell lysate protein (20 μg) and supernatant (30 μg) were fractionated on 4% to 15% Mini-PROTEAN TGX Precast Gel (Bio-Rad Laboratories) and transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to a PVDF membrane using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) and transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to a PVDF membrane using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) and transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories) or transferred to Trans-Blot Turbo Mini PVDF Transfer Packs (Bio-Rad Laboratories) using a Trans-Blot Turbo Transfer Starter System (Bio-Rad Laboratories). The membranes were incubated overnight at 4°C with anti-TGF-β1 (sc-146; 1:200), anti-PDGF-A (sc-128; 1:200), anti-PDGF-B (sc-127; 1:200), anti-CTGF (sc-101586; 1:200), anti-HGF (sc-13087; 1:200), anti-VEGF (sc-152; 1:200), anti-FGF-2 (sc-79; 1:200), anti-collagen type I (sc-8783; 1:1000), anti-fibronectin (sc-6952; 1:1000), anti-periostin (sc-67233; 1:1000) antibodies (Santa Cruz Biotechnology); anti-α-SMA (1:500; DAKO), rabbit polyclonal anti-periostin (sc-67233; 1:500; Santa Cruz Biotechnology), mouse monoclonal anti-cytokeratin 19 (sc-376126; 1:100), and rabbit polyclonal anti-fibronectin (ab2426; 1:500; abcam). The α-SMA–positive cells were counted in 3 fields at a magnification of ×100 under a light microscope. The PCNA index (%) was calculated as (PCNA-positive tumor stained area/total tumor stained area) × 100 under a light microscope.

**Sirus red staining and measurements**

Sections were stained using a Picosirius Red Staining Kit (Polysciences Inc.) according to manufacturer’s instructions. The Sirius red–stained area was measured using Adobe Photoshop CS (Adobe Systems Incorporated) by selecting stained fibers in three fields at a magnification of ×100 under a light microscope.

**Statistical analysis**

Results are expressed as means ± SD. Comparisons between groups were evaluated by one-way ANOVA test followed by the Tukey–Kramer multiple comparisons test. Values of *P* < 0.05 were considered statistically significant in all analyses. All statistical analyses were conducted using JMP 8.01 software (SAS Institute).

**Results**

**Pirfenidone decreases the proliferation, invasion, and migration of PSCs**

Pirfenidone inhibited the proliferation of PSCs in a dose-dependent manner (*P* < 0.05, Fig. 1A). Although pirfenidone also inhibited PCCs, SUIT-2 cells, and Mia PaCa-2 cells in a dose-dependent manner, low concentrations of pirfenidone, particularly 0.3 mg/mL, showed greater inhibitory activity on PSCs than on PCCs. Pirfenidone significantly decreased the invasion and migration of PSCs at concentrations of 0.1 and 0.3 mg/mL but did not affect PCCs (*P* < 0.05, Fig. 1B–E). These data indicate that PSCs are more
strongly affected by pirfenidone than are PCCs and suggest that pirfenidone exerts antitumor effects on pancreatic cancer by inhibiting the interaction between PSCs and PCCs. To investigate the specific effects of pirfenidone on PSCs, we used 0.3 mg/mL pirfenidone in the following in vitro experiments.

Pirfenidone suppresses PSCs by disrupting tumor–stromal interactions

It was reported that the biologic activities of PSCs, such as proliferation and invasion, are potentiated by tumor–stromal interactions. Therefore, we investigated the effects of pirfenidone on the tumor–stromal interactions of PSCs using SUIT-2-

Figure 1. A, effects of pirfenidone on the proliferation of PSCs (PSC1-3 cells) and PCCs (SUIT-2 and MIA PaCa-2 cells). Pirfenidone dose dependently inhibited the proliferation of PSCs and PCCs. Low concentrations of pirfenidone, particularly 0.3 mg/mL, showed stronger inhibitory effects on PSCs than PCCs. \( * P < 0.05 \) for PSCs versus PCCs treated with 0.3 mg/mL pirfenidone. B, pirfenidone dose dependently decreased the invasiveness of PSCs but not of SUIT-2 or MIA PaCa-2 cells. C, representative photomicrographs of invading PSCs and PCCs. D, pirfenidone dose dependently decreased the migration of PSCs but not of SUIT-2 or MIA PaCa-2 cells. E, representative photomicrographs of migrating PSCs and PCCs. \( * P < 0.05 \). H&E; original magnification, ×100; scale bars, 200 μm.
Stimulation with SUIT-2-SN significantly increased the proliferation ($P < 0.05$, Fig. 2A), invasiveness ($P < 0.05$, Fig. 2B and C), and migration ($P < 0.05$, Fig. 2D and E) of PSCs. Pirfenidone significantly decreased these effects of SUIT-2-SN on the proliferation, invasiveness, and migration of PSCs (all $P < 0.05$). These results suggest that pirfenidone suppresses PSCs by disrupting the tumor–stromal interactions.

**Pirfenidone inhibits the stimulatory effects of PSC supernatants on PCCs**

To determine the effects of pirfenidone on the tumor–stromal interactions between PSCs and PCCs, we prepared PSC supernatant (PSC-SN), PSC-SN supplemented with pirfenidone (PSC-SN + pirfenidone), and pirfenidone-treated PSC-SN. PSC-SN increased the proliferation of PCCs (SUIT-2 cells and MIA PaCa-2 cells, $P < 0.05$, Fig. 3A). In contrast, pirfenidone-treated PSC-SN did not enhance the proliferation of PCCs compared with PSC-SN and PSC-SN + pirfenidone. Similarly, pirfenidone-treated PSC-SN decreased the ability of PSCs to enhance the invasiveness and migration of PCCs ($P < 0.05$, Fig. 3B–E). These findings suggest that pirfenidone may suppress the production of factors involved in tumor–stromal interactions in PSC-SN.

**Pirfenidone decreases the mRNA and protein expression of genes involved in tumor–stromal interactions in PSCs**

To assess the mechanism by which pirfenidone suppresses tumor–stromal interactions, we determined the expression of the major factors involved in these interactions by qRT-PCR and Western blotting of whole-cell lysates and PSC-SN. PSCs derived from pancreatic cancer tissues secreted PDGF-A, HGF, FGF-2, CTGF, and ECM proteins including collagen type I, fibronectin, and periostin. Treatment with pirfenidone significantly reduced the protein and mRNA expression of PDGF-A, HGF, and periostin in PSCs (Fig. 4). Next, we analyzed the effects of SUIT-2-SN and pirfenidone on PSC protein production and tumor–stromal interactions. Exposure to SUIT-2-SN considerably enhanced the synthesis and secretion of PDGF-A, HGF, collagen type I, fibronectin, and periostin, which were inhibited by pirfenidone. Pirfenidone also decreased mRNA, but not protein, $\alpha$-SMA expression in PSCs. These findings indicate that pirfenidone disrupts tumor–stromal interactions by suppressing the synthesis and secretion of factors involved in these interactions, particularly PDGF-A, HGF, periostin, collagen type I, and fibronectin.

**Pirfenidone inhibits subcutaneous tumor formation in vivo in mice co-transplanted with SUIT-2 cells and PSCs**

To examine the effects of pirfenidone on PCCs and PSCs in vivo, we transplanted nude mice with SUIT-2 cells and PSCs into the right flank and SUIT-2 cells alone into the left flank (Fig. 5A). One week after implantation, we started oral administration of pirfenidone daily for 5 weeks, whereas a control group was administered with sterile water. In the control group, tumor growth was much greater with co-implantation.

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Figure 2. Effects of pirfenidone on PSCs stimulated with SUIT-2-SN. A, exposure to SUIT-2-SN enhanced the proliferation of PSCs compared with control cells. Pirfenidone also suppressed the effects of SUIT-2-SN on PSC proliferation. B and D, PSC invasiveness (B) and migration (D) were significantly increased by SUIT-2-SN and were suppressed by pirfenidone. C and E, representative photomicrographs of invading (C) and migrating (E) PSCs. H&E; original magnification, $\times$100; scale bars, 200 $\mu$m. *, $P < 0.05$. SN. Stimulation with SUIT-2-SN significantly increased the proliferation ($P < 0.05$, Fig. 2A), invasiveness ($P < 0.05$, Fig. 2B and C), and migration ($P < 0.05$, Fig. 2D and E) of PSCs. Pirfenidone significantly decreased these effects of SUIT-2-SN on the proliferation, invasiveness, and migration of PSCs (all $P < 0.05$). These results suggest that pirfenidone suppresses PSCs by disrupting the tumor–stromal interactions.
of SUIT-2 cells and PSCs compared with SUIT-2 cells alone (P < 0.05, Fig. 5A and B). The tumors consisting of SUIT-2 cells co-implanted with PSCs showed marked desmoplasia with larger Sirius red–positive areas and more α-SMA–positive cells than the tumors consisting of SUIT-2 cells alone (P < 0.05, Fig. 5C–E; Supplementary Fig. S2). Treatment with pirfenidone significantly suppressed the growth of tumors consisting of SUIT-2 cells co-implanted with PSCs compared with that in the control group (P < 0.05, Fig. 5B). Pirfenidone also reduced the Sirius red–positive area and the number of α-SMA–positive cells in tumors consisting of SUIT-2 cells co-implanted with PSCs (P < 0.05, Fig. 5C–E). In contrast, tumor growth of SUIT-2 cells alone was not significantly different between the pirfenidone-treated and control groups. Pirfenidone significantly reduced the PCNA index in tumors consisting of SUIT-2 cells co-implanted with PSCs (P < 0.05, Fig. 5F). However, the PCNA index was not significantly different between the control group and the pirfenidone group in tumors consisting of SUIT-2 cells alone (P = 0.98, Fig. 5F). Periostin expression was only detected immunohistochemically in the control tumors consisting of SUIT-2 cells co-implanted with PSCs (Fig. 5C). These findings suggest that, at the concentration used in this experiment, pirfenidone indirectly, rather than directly, targets pancreatic cancer cells (i.e., SUIT-2 cells) by suppressing the growth/proliferation of PSCs and by suppressing ECM deposition.

The inhibitory effects of pirfenidone on the growth and metastasis of tumors consisting of SUIT-2 cells co-implanted with PSCs are enhanced by combination treatment with gemcitabine

We next investigated the effects of pirfenidone alone or in combination with gemcitabine on growth and metastasis of orthotopic tumors in mice. The administration of pirfenidone and gemcitabine was started 1 week after tumor implantation. Pirfenidone significantly inhibited the growth of orthotopic tumors consisting of SUIT-2 cells co-implanted with PSCs, as observed in mice with subcutaneous tumors (P < 0.05, Fig. 6A and B; Supplementary Fig. S3B). Although gemcitabine alone inhibited the growth of orthotopic tumors consisting of SUIT-2 cells co-implanted with PSCs, the suppressive effects were significantly greater when gemcitabine was administered in combination with pirfenidone (P < 0.05). Immunohistologic studies showed that pirfenidone significantly suppressed the desmoplastic reactions in orthotopic tumors whereas gemcitabine did not (P < 0.05, Fig. 6C and D; Supplementary Fig. S3A). Although the orthotopic mice showed evidence of peritoneal dissemination and liver metastasis, pirfenidone decreased the number of peritoneal disseminated nodules and the incidence of liver metastasis. These suppressive effects of pirfenidone where significantly enhanced by combination with gemcitabine (P < 0.05, Fig. 6E and F; Supplementary Fig. S3C; Table 1).
These findings suggest that pirfenidone can suppress tumor growth and metastasis of orthotopic tumors consisting of SUIT-2 cells co-implanted with PSCs and that combination treatment with gemcitabine has synergistic effects on these tumors.

**Discussion**

We showed that PSCs increased the biologic activities and augmented the production of PDGF-A, HGF, collagen type I, fibronectin, and periostin through tumor–stromal interactions with PCCs. In addition, we found that pirfenidone strongly suppressed the activities of PSCs by disrupting the tumor–stromal interactions and significantly inhibited the production of these factors. These factors play critical roles in the tumor–stromal interactions in pancreatic cancer. PDGF was reported to induce the proliferation and migration of PSCs through paracrine and autocrine pathways (24–27). We previously reported that irradiated stromal fibroblasts increased the invasiveness of PCCs through the HGF–c-Met pathway (21). Ide and colleagues (28) reported that HGF secreted from fibroblasts under hypoxic conditions increased the invasiveness of PCCs. ECM components, including collagen type I, fibronectin, and periostin, were reported to augment the proliferation of PCCs. PDGF-A was reported to induce the proliferation and migration of PSCs through paracrine and autocrine pathways (24–27).

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**Figure 4.** Effects of pirfenidone on gene and protein expression levels of growth factors and ECM proteins associated with tumor–stromal interactions. PSCs were untreated or treated with pirfenidone, SUIT-2-SN, or SUIT-2-SN + pirfenidone. mRNA expression levels were normalized to 18S rRNA expression and are presented as the fold change in gene expression relative to control PSCs. Protein expression of growth factors was analyzed by Western blotting of the supernatants of PSCs. Western blotting of ECM proteins and α-SMA was conducted using whole-cell lysates and the supernatant of PSCs. α-Tubulin was used as a control to confirm equal protein loading in each well for analysis of cell lysates. The densitometric data are presented as the fold change relative to control PSCs.
A Control group Pirfenidone group
Left tumor; SUIT-2 cells
Right tumor; SUIT-2 cells + PSCs

B
Day 0 Administration starts
Day-7 Implantation

Subcutaneous tumor volume (mm³)
Days after the beginning of treatment

SUIT-2+PSCs/control
SUIT-2+PSCs/pirfenidone
SUIT-2/control
SUIT-2/pirfenidone

D
Percentage sirius red positive area ×100 field (%)

E
Number of α-SMA positive cells ×100

F
PCNA Index (%)

C
HE Cytokeratin 19 Sirius red α-SMA Periostin PCNA

Control
SUIT-2
Pirfenidone

Control
Pirfenidone

Control
SUIT-2+PSCs
Pirfenidone

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Cancer Res; 73(7) April 1, 2013

Published OnlineFirst January 24, 2013; DOI: 10.1158/0008-5472.CAN-12-3180

and migration of PCCs and enhance their resistance to anti-cancer drugs (29–33). Consistent with these reports, PSC-SN greatly increased the malignant potential of PCCs. Meanwhile pirfenidone-treated PSC-SN decreased the ability of PSCs to enhance the invasiveness and migration of PCCs in our study. The antitumor effects of pirfenidone may involve suppression of the biologic activation of PSCs and attenuation of the tumor–stromal interactions by suppressing the production of PDGF-A, HGF, collagen type I, fibronectin, and peristin.

Figure 5. Antitumor effects of pirfenidone on subcutaneous tumor formation in vivo. SUIT-2 cells plus PSCs (right flank) or SUIT-2 cells alone (left flank) were subcutaneously implanted into nude mice (n = 15 mice/group). From 1 week after implantation, the mice were orally administered with pirfenidone daily for 5 weeks. A, representative photographs showing the effects of pirfenidone on tumor formation. B, time course of tumor growth. C, histologic evaluation of desmoplastic activity. Periostin staining was more intense in tumors consisting of SUIT-2 cells co-implanted with PSCs than in tumors consisting of SUIT-2 cells alone. Pirfenidone significantly decreased the Sirius red-positive area in tumors consisting of SUIT-2 cells co-implanted with PSCs. E, the number of α-SMA-positive cells was higher in tumors consisting of SUIT-2 cells co-implanted with PSCs than in tumors consisting of SUIT-2 cells in the control group. Pirfenidone decreased the number of α-SMA-positive cells in tumors consisting of SUIT-2 cells co-implanted with PSCs. The α-SMA-positive cells in tumors consisting of SUIT-2 cells alone probably originated from the host, and their number was decreased by pirfenidone. F, the PCNA index (%) was decreased by pirfenidone in tumors consisting of SUIT-2 cells co-implanted with PSCs but not in tumors consisting of SUIT-2 cells alone. *P < 0.05.

Figure 6. Antitumor effects of pirfenidone and/or gemcitabine on orthotopic pancreatic cancer mouse models. SUIT-2 cells and PSCs were co-implanted into the tail of the pancreas of nude mice (n = 12 mice/group). Starting 1 week after orthotopic implantation of SUIT-2 cells and PSCs, mice were intravenously injected with gemcitabine weekly and orally administered with pirfenidone daily for 5 weeks. A, representative photographs showing the effects of gemcitabine in combination with pirfenidone. B, pirfenidone in combination with gemcitabine significantly suppressed the growth of tumors consisting of SUIT-2 cells co-implanted with PSCs. The Sirius red-positive area (C) and the number of α-SMA-positive cells (D) were decreased in mice treated with pirfenidone alone but not in mice treated with gemcitabine alone. E, representative photographs showing metastasis in the peritoneal cavity of mice after the indicated treatments (arrowhead). F, pirfenidone decreased the number of disseminated visible nodules larger than 1 mm in size, and this suppressive effect was enhanced by combination treatment with gemcitabine. *P < 0.05.
For the first time, we found that pirfenidone significantly suppressed the production of periostin by PSCs. Periostin, originally called osteoblast-specific factor 2, is a 93.3-kDa secreted protein involved in the recruitment and attachment of osteoblast precursors in the peristeum (34, 35). Periostin is predominantly expressed in collagen-rich fibrous connective tissues in several organs, where it regulates collagen fibrillogenesis (36). Recent studies have revealed that periostin is overexpressed in the stroma of several types of cancer including ovarian cancer, non–small cell lung cancer, colon cancer, prostate cancer, and pancreatic cancer (37). Periostin promoted tumor growth and metastasis and was associated with poor prognosis of patients with these cancers. Erkan and colleagues (33) reported that once PSCs are activated by PCCs, the PSCs remained active via an autocrine periostin loop, and produced excessive ECM creating a tumor-supportive microenvironment. Recently, periostin was reported to maintain cancer stem cells by increasing Wnt signaling and facilitate metastatic colonization (38). Zhu and colleagues reported that a neutralizing monoclonal antibody to periostin could inhibit ovarian cancer, non–small cell lung cancer, colon cancer, small cell lung cancer, and prostate cancer xenografts. Therefore, combining pirfenidone with gemcitabine significantly suppressed the growth of SUIT-2 cells co-implanted with PSCs compared with treatment with gemcitabine alone. Histologic examination of the orthotopic tumors revealed that pirfenidone, but not gemcitabine, decreased desmoplastic reactions, as observed in subcutaneous tumors. These results suggest that co-administration of gemcitabine, which targets cancer cells, and pirfenidone, which targets desmoplastic activity, have synergistic antitumor effects. Therefore, this combination may represent an ideal treatment strategy for pancreatic cancer associated with excessive desmoplasia.

In conclusion, the present study revealed that pirfenidone inhibits the biologic activity of PSCs. Pirfenidone also inhibited the production of PDGF-A, HGF, collagen type I, fibronectin, and periostin, factors that play important roles in tumor–stromal interactions in pancreatic cancer. Pirfenidone and gemcitabine had synergistic antitumor effects on pancreatic cancer xenografts. Therefore, combining pirfenidone with traditional anticancer drugs such as gemcitabine may offer a promising treatment strategy for pancreatic cancer.

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

Authors’ Contributions
Conception and design: S. Kozono, K. Ohuchida, D. Eguchi, K. Mizumoto
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Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): S. Kozono, K. Ohuchida, N. Ikenaga, K. Fujitawa
Writing, review, and/or revision of the manuscript: S. Kozono, K. Ohuchida, N. Ikenaga, K. Mizumoto, M. Tanaka
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Study supervision: K. Ohuchida, M. Tanaka

Table 1. Effects of pirfenidone and/or gemcitabine on orthotopic mouse models of pancreatic cancer

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<th>Group</th>
<th>Incidence of macroscopic tumors</th>
<th>Tumor weight (mean ± SD), g</th>
<th>Body weight (mean ± SD), g</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Pancreatic tumor</td>
<td>Peritoneal dissemination</td>
<td>Liver metastasis</td>
</tr>
<tr>
<td>Control</td>
<td>12/12</td>
<td>9/12</td>
<td>6/12</td>
</tr>
<tr>
<td>Pirfenidone</td>
<td>12/12</td>
<td>3/12</td>
<td>1/12</td>
</tr>
<tr>
<td>Gemcitabine</td>
<td>12/12</td>
<td>8/12</td>
<td>3/12</td>
</tr>
<tr>
<td>Pirfenidone plus</td>
<td>12/12</td>
<td>1/12</td>
<td>0/12</td>
</tr>
<tr>
<td>gemcitabine</td>
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</tbody>
</table>

Published OnlineFirst January 24, 2013; DOI: 10.1158/0008-5472.CAN-12-3180
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Received August 13, 2012; revised January 10, 2013; accepted January 12, 2013; published OnlineFirst January 24, 2013.

Acknowledgments

The authors thank M. Ohnori and E. Manabe (Department of Surgery and Oncology, Kyushu University Hospital) for their expert technical assistance.

Grant Support

This work was supported in part by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT; KAKENHI grants 23390327, 24659613, 23590319, 2365964, 24390318, and 23659655).

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Cancer Res; 73(7) April 1, 2013 2355

Published OnlineFirst January 24, 2013; DOI: 10.1158/0008-5472.CAN-12-3180

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