Antifibrotic Effect of Pirfenidone on Orbital Fibroblasts of Patients with Thyroid-Associated Ophthalmopathy by Decreasing TIMP-1 and Collagen Levels

Hyunmi Kim,1,2 Youn-Hee Choi,3,5 Soo Jung Park,1,2 Sang Yeul Lee,4 Sung Joo Kim,5 Illo Jou,1,2 and Koung Hoon Kook1,2

PURPOSE. The aim of this study was to determine the antifibrotic effects of pirfenidone in orbital fibroblasts of patients with thyroid-associated ophthalmopathy (TAO).

METHODS. The effects of interleukin (IL)-1β and of fibroblast growth factor (FGF), platelet-derived growth factor (PDGF), and transforming growth factor (TGF)-β on the induction of tissue inhibitors of metalloproteinases (TIMPs) were measured in orbital fibroblasts of TAO patients. TIMP-1 protein levels were measured by ELISA and Western blot analyses, and TIMP-1 activity was assessed by reverse zymography. The effect of pirfenidone on TIMP-1 induction in orbital fibroblasts was evaluated with the same methods using dexamethasone as a reference agent. A hydroxyproline assay was used to determine the effect of pirfenidone and dexamethasone on collagen production in orbital fibroblasts, and the tetrazolium-based MTT assay was used to assess pirfenidone cytotoxicity.

RESULTS. IL-1β strongly and dose dependently increased the level of active TIMP-1 protein, whereas FGF, PDGF, and TGF-β did not significantly induce TIMP-1 protein. Pirfenidone was more effective than dexamethasone in inhibiting IL-1β-induced increases in TIMP-1, reducing TIMP-1 levels to less than those in untreated controls at a minimal concentration (5 mM). Moreover, pirfenidone effectively decreased hydroxyproline levels in orbital fibroblasts, whereas dexamethasone had no effect on hydroxyproline levels. Pirfenidone exhibited no toxicity in orbital fibroblasts at the concentrations used.

CONCLUSIONS. These results indicate that nontoxic concentrations of pirfenidone have significant antifibrotic effects on orbital fibroblasts from patients with TAO. (Invest Ophthalmol Vis Sci. 2010;51:3061–3066) DOI:10.1167/iovs.09-4257

Disclosure: H. Kim, None; Y.-H. Choi, None; S.J. Park, None; S.Y. Lee, None; S.J. Kim, None; I. Jou, None; K.H. Kook, None

Supported by Korea Science and Engineering Foundation Grant R13-2005-019-0100-0 funded by the Korean government and by Grant 3-2008-006-0 from Ajou University School of Medicine.

Submitted for publication July 1, 2009; revised November 3 and December 7, 2009; accepted December 22, 2009.

This study is the first to evaluate the antifibrotic effects of pirfenidone in orbital fibroblasts in TAO.
TABLE 1. Characteristics of TAO Patients and Control Patients without Inflammatory Disease from Whom Fibroblast Strains Were Obtained

<table>
<thead>
<tr>
<th></th>
<th>Patients with TAO (n = 6)</th>
<th>Control Patients without TAO (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age, y (range)</td>
<td>41 (29–61)</td>
<td>45 (21–67)</td>
</tr>
<tr>
<td>Sex, m/f</td>
<td>4/2</td>
<td>2/4</td>
</tr>
<tr>
<td>Smoking, yes/no</td>
<td>1/6</td>
<td>2/6</td>
</tr>
<tr>
<td>Graves’ disease</td>
<td>6/6</td>
<td>0/6</td>
</tr>
<tr>
<td>Radioactive iodine therapy</td>
<td>0/6</td>
<td>—</td>
</tr>
<tr>
<td>Surgery</td>
<td>1/6</td>
<td>—</td>
</tr>
<tr>
<td>Methimazole</td>
<td>5/6</td>
<td>—</td>
</tr>
<tr>
<td>Treatment TAO</td>
<td>6/6</td>
<td>0/6</td>
</tr>
<tr>
<td>Surgery</td>
<td>6/6</td>
<td>—</td>
</tr>
<tr>
<td>Prednisone</td>
<td>4/6</td>
<td>—</td>
</tr>
<tr>
<td>Radiation</td>
<td>0/6</td>
<td>—</td>
</tr>
<tr>
<td>Euthyroid</td>
<td>5/6</td>
<td>6/6</td>
</tr>
<tr>
<td>TSH-receptor antibodies</td>
<td>6/6</td>
<td>0/6</td>
</tr>
<tr>
<td>Clinical activity score (range)</td>
<td>3 (1–5)</td>
<td>—</td>
</tr>
</tbody>
</table>

MATERIALS AND METHODS

Cell Culture

Human orbital fibroblasts were cultivated from orbital fatty connective tissue obtained as surgical waste during decompression surgery for severe TAO or during orbital surgery to resolve noninflammatory conditions. These activities were undertaken after informed consent was obtained from the donors according to procedures approved by the Institutional Review Board of Ajou University Hospital and the tenets of the Declaration of Helsinki. Six different orbital fibroblast culture strains were obtained from each of six individual patients with TAO and six control patients without TAO. At the point of decompression surgery, five patients were euthyroid; one was in a hypothyroid state because of previous total thyroidectomy. Four patients had been administered prednisone therapy (1 mg/kg for 3 days followed by tapering of dose over 4 to 8 weeks) for their previous active disease, and all six patients had experienced at least 6 months of inactive disease and no corticosteroid therapy before orbital decompression. Patient characteristics are presented in Table 1. Once obtained, cells were maintained in Dulbecco’s modified essential medium (DMEM; HyClone, Logan, UT) containing 10% (vol/vol) fetal bovine serum (FBS; HyClone) and antibiotics in a humidified 5% CO2 incubator at 37°C.

Enzyme-Linked Immunosorbent Assay

TIMP-1 protein levels in cell culture supernatants of orbital fibroblasts were measured in cells seeded in six-well culture plates at a final concentration of 5 × 105 cells/well. After stabilization for 48 hours, cells were treated with IL-1β (Biosource, Camarillo, CA) or growth factors (fibroblast growth factor [bFGF], Biosource), platelet-derived growth factor (PDGF)-BB (Biosource), and transforming growth factor (TGF)-β1 (R&D Systems, Minneapolis, MN). In some experiments, cells were cotreated with IL-1β and pirfenidone (Sigma-Aldrich, St. Louis, MO) or dexamethasone (Sigma-Aldrich), as described. After treatment for 48 hours, the concentration of TIMP-1 in supernatants was determined using a sandwich ELISA method. Briefly, 96-well plates were precoated overnight at room temperature with a capture antibody (R&D Systems). After three washes, plates were blocked with phosphate-buffered saline (PBS; pH 7.4) containing 5% (vol/vol) sucrose and 1% (wt/vol) bovine serum albumin, followed by incubation with detection antibody (R&D Systems). After washing, plates were incubated with horseradish peroxidase (HRP)-conjugated secondary antibody for 20 minutes and then incubated with color reagents A (substrate, hydrogen peroxide) and B (tetramethylbenzidine; R&D Systems) for 30 minutes. Absorbance was measured spectrophotometrically at 540 nm using a microplate reader (Molecular Devices, Sunnyvale, CA). The concentration of TIMP-1 in each sample was determined by reference to a standard curve generated using known amounts of TIMP-1 (R&D Systems).

Western Blot Analysis

TIMP-1 protein levels in supernatants of orbital fibroblasts (5 × 105 cells/well), cultured and treated as described for ELISA, were measured by immunoblotting. After treating fibroblasts for 48 hours, supernatants (normalized for cell numbers) were solubilized in 5 × Laemmli buffer. Proteins were separated by SDS-PAGE on 12% (wt/vol) gels and transferred to nitrocellulose membranes (Schleicher & Schuell BioScience, Keene, NH). Each membrane was blocked by incubation at room temperature for 1 hour with Tris-buffered saline (TBS; pH 7.4) containing 5% (vol/vol) skim milk and then was incubated at 4°C overnight with anti-TIMP-1 antibody. After three washes with TBST (TBS containing 0.1% [vol/vol] Tween-20), membranes were incubated with HRP-conjugated anti-mouse secondary antibodies, and immunoreactive proteins were detected by incubation with Western blot substrate (AbFrontier, Seoul, Korea) followed by exposure to X-ray film.

Reverse Zymography

Orbital fibroblasts (5 × 105 cells/well) were seeded in six-well cell culture plates and treated according to the same protocol used for ELISA. After incubation for 24 hours, supernatants were collected and assayed by reverse zymography as described previously,7 with minor modifications. Briefly, supernatants were diluted (with normalization for cell number), solubilized in 5 × Laemmli buffer, and separated by electrophoresis on gels prepared to contain MMP-9 (20 ng/mL). Gels were shaken for 1 hour in 2.5% (vol/vol) Triton X-100 after electrophoresis, washed in distilled water, and incubated overnight in developing solution at 37°C. Gels were then washed in distilled water, stained with Coomassie Brilliant Blue for 2 hours, and incubated with shaking in destaining solution.

Cytotoxicity Assay

Cell growth and death were assessed using 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT; Sigma-Aldrich) assays. Orbital fibroblasts (1 × 105) were seeded into 24-well culture plates and treated according to the same protocol used for ELISA. After washing cells with PBS (pH 7.4), 50 μL MTT solution (1 mg/mL in PBS) was added to each well, and plates were incubated for 4 hours at 37°C. Plates were then centrifuged at 3000g for 10 minutes, the supernatant was carefully removed, and the remaining adherent cells were dissolved in 200 μL dimethyl sulfoxide (DMSO). Optical density was measured at 570 nm using a microplate reader.

Hydroxyproline Assay

Total collagen production was assessed by measuring hydroxyproline levels in culture media using a hydroxyproline assay kit (Nanjing Jiancheng Biochemical Institute, Nanjing City, P.R. China) according to the manufacturer’s instructions. Briefly, cells were seeded in six-well culture plates at a final density of 1 × 106 cells/well and were allowed to stabilize for 48 hours. After treatment with IL-1β or pirfenidone (or both) or dexamethasone for 48 hours, the levels of hydroxyproline in culture media were measured.

Statistical Analysis

Tukey’s HSD tests were used in analyzing the stimulatory effects of IL-1β, FGF, PDGF, or TGF-β on TIMP-1 production and the inhibitory effects of pirfenidone or dexamethasone on TIMP-1 or collagen production. The effect of pirfenidone on the viability of cells was analyzed using a one-way analysis of variance (ANOVA) test. P < 0.05 was considered statistically significant.
RESULTS

Increase of TIMP-1 Protein by IL-1β in Orbital Fibroblasts

We initially examined the influence of IL-1β and three other growth factors, FGF, PDGF, and TGF-β, on TIMP-1 levels in human orbital fibroblasts of patients with TAO. Cells were treated with 10 ng/mL of each cytokine or growth factor for 48 hours, and TIMP-1 protein levels in culture media were analyzed by ELISA, as described in Materials and Methods. IL-1β induced a marked increase in TIMP-1 protein levels that reached nearly 2.5-fold that of controls; in contrast, the addition of FGF, PDGF, or TGF-β did not substantially increase TIMP-1 levels (Fig. 1A). TIMP-1 protein levels were also increased in orbital fibroblasts of normal tissue, but to a much lesser extent (1.2-fold compared with control) than in those of TAO patients (Fig. 1B). Therefore, subsequent experiments were performed using orbital fibroblasts of TAO patients. Incubation of such cells for 48 hours with a range of IL-1β concentrations (1–20 ng/mL) caused a dose-dependent increase in TIMP-1 (Fig. 2A). The increase in TIMP-1 levels after treatment with 10 ng/mL IL-1β was verified by immunoblotting (Fig. 2B). This increase in TIMP-1 protein was associated with an increase in enzymatic activity, as revealed by reverse zymography analysis (Fig. 2C).

Attenuation of TIMP-1 by Pirfenidone in Orbital Fibroblasts

To examine the effects of pirfenidone on the IL-1β-induced increase in TIMP-1 level, we cotreated orbital fibroblasts with different concentrations of pirfenidone and 10 ng/mL IL-1β and measured the levels of TIMP-1 in culture media by ELISA. Guided by a previous in vitro study showing an antifibrotic effect of pirfenidone in human Tenon’s fibroblasts at concentrations up to 1 mg/mL (5.4 mM),20 we used pirfenidone at 1, 5, and 10 mM. As shown in Figure 3A, pirfenidone significantly attenuated the IL-1β-induced TIMP-1 increase at concentrations of 5 and 10 mM, decreasing TIMP-1 protein concentrations to 18% and 14% of the values obtained after IL-1β stimulation. Strikingly, the levels of TIMP-1 protein in cells treated with these two concentrations of pirfenidone were lower than those in non-IL-1β-treated control cells (44% and 34% of control values at 5 and 10 mM, respectively). This inhibitory effect of pirfenidone on the IL-1β-induced TIMP-1 increase was verified by immunoblotting (Fig. 3B).

Effect of Pirfenidone on the Viability of Orbital Fibroblasts

MTT assays were performed to analyze pirfenidone toxicity and to clarify whether the effects reported could have been influenced by harmful pirfenidone side effects. As shown in Figure 4, the viability of primary orbital fibroblasts was not affected by 48-hour incubation with pirfenidone at concentrations of up to 10 mM.

Comparative Efficacy of Pirfenidone and Dexamethasone in Decreasing of TIMP-1 in Orbital Fibroblasts

In light of a previous report that dexamethasone attenuates IL-1β–induced increases in TIMP-1 levels,22 we compared the inhibitory efficacy of pirfenidone on TIMP-1 expression with
that of dexamethasone. After cotreating orbital fibroblasts with 10 ng/mL IL-1β and 10 mM pirfenidone or 100 nM dexamethasone for 48 hours, TIMP-1 levels in the culture medium were measured by ELISA. As shown in Figure 5A, the inhibitory effect of pirfenidone on IL-1β-induced TIMP-1 upregulation (52% reduction of IL-1β-induced levels) was significantly greater than that of dexamethasone (42% reduction of IL-1β-induced levels). Pirfenidone also inhibited TIMP-1 expression in orbital fibroblasts not treated with IL-1β; again, the inhibitory effect of pirfenidone (76% reduction compared with untreated control) was significantly greater than that of dexamethasone (45% reduction compared with untreated control).

To confirm the inhibitory effects of pirfenidone and dexamethasone on TIMP-1 expression, we immunoblotted the culture media for TIMP-1 protein after treating cells as described for the experiment in Figure 5A. Consistent with the ELISA results, Western blot analysis showed that the inhibitory effect of pirfenidone on TIMP-1 protein levels was significantly greater than that of dexamethasone (Fig. 5B). The 28-kDa band of TIMP-1 protein that was evident in culture medium was not detectable in whole-cell lysates analyzed by immunoblotting (data not shown).

**Effect of Pirfenidone on Collagen Production in Orbital Fibroblasts**

To evaluate the effect of pirfenidone on collagen production in orbital fibroblasts, we assayed cell cultures for hydroxyproline content, as described in Materials and Methods. After cotreatment of orbital fibroblasts with 10 ng/mL IL-1β and 10 mM pirfenidone or 100 nM dexamethasone for 48 hours, the level of hydroxyproline in cell culture medium was measured. Cells treated with 10 mM pirfenidone or 100 nM dexamethasone only, without IL-1β, were also included in the assay to determine the separate effects of these agents on the basal level of collagen produced by fibroblasts. As shown in Figure 6, in both IL-1β-treated and untreated orbital fibroblasts, pirfenidone significantly decreased the expression of hydroxyproline, reducing hydroxyproline levels to 41% and 44% of control levels, respectively. In contrast, dexamethasone had no significant inhibitory effect in IL-1β-treated or untreated fibroblasts. Notably, in contrast to the significant effect of IL-1β on the induction of TIMP-1 expression shown, the difference in hydroxyproline content between IL-1β-treated and untreated fibroblasts did not reach statistical significance.
stimulate the inflammatory response in dermal fibroblasts.\(^\text{27,28}\) Important roles in orbital inflammatory responses but do not potentiate the induction of orbital fibroblast genes that play neuroectoderm.\(^\text{26}\) Orbital fibroblasts have unique site-specific mesoderm, orbital fibroblasts are known to originate from the site of TIMP-1 levels in orbital fibroblasts. Interestingly, none of these three growth factors produced a noticeable effect on TIMP-1.\(^\text{13}\) In agreement with this previous report, our results demonstrated that IL-1\(\beta\) is a potent inducer of TIMP-1 in orbital fibroblasts. A number of in vitro studies have demonstrated that various stimulants increase TIMP-1 in other types of cells, such as bFGF in lung fibroblasts.\(^\text{23}\) PDGF-BB in chondrocytes.\(^\text{24}\) and TGF-\(\beta\)1 in mesothelial cells.\(^\text{25}\) However, in our hands, none of these three growth factors produced a noticeable effect on TIMP-1 levels in orbital fibroblasts. Interestingly, unlike other site-specific fibroblasts that are derived from the mesoderm, orbital fibroblasts are known to originate from the neuroectoderm.\(^\text{26}\) Orbital fibroblasts have unique site-specific characteristics compared with other types of fibroblasts.\(^\text{1}\) Proinflammatory cytokines, such as leukoregulin and IL-1\(\beta\), potentiate the induction of orbital fibroblast genes that play important roles in orbital inflammatory responses but do not stimulate the inflammatory response in dermal fibroblasts.\(^\text{27,28}\) Such site-specific characteristics of orbital fibroblasts may be relevant to our results.

In addition, unlike some fibroblasts, orbital fibroblasts display cell surface expression of CD40, a receptor originally described in B lymphocytes.\(^\text{79}\) The level of CD40 in TAO orbital fibroblasts is high compared with that in normal orbital fibroblasts.\(^\text{29}\) Activation of CD40 by its ligand, CD154, on the surfaces of T lymphocytes promotes the upregulation of several inflammatory cytokines, including IL-6, IL-8, and macrophage chemotactrant protein-1, exclusively in TAO orbital fibroblasts.\(^\text{29}\) Consistent with these TAO-dependent differences in orbital fibroblast behavior, our study showed that the IL-1\(\beta\)-induced increase in TIMP-1 was significantly greater in orbital fibroblast of TAO patients than in those of controls without TAO.

Controlling a pathologic increase in TIMP levels could be a novel therapeutic strategy for halting the progression of fibrosis. In an animal model of chronic liver disease characterized by the development of hepatic fibrosis, TIMP-1 promoted liver fibrosis in association with decreased levels of the active form of MMP-2.\(^\text{30}\) and fibrosis regression was achieved by neutralization of TIMP-1.\(^\text{12}\) In the present study, we showed that pirfenidone effectively decreased TIMP-1 protein levels not only in IL-1\(\beta\)-treated orbital fibroblasts but also in untreated orbital fibroblasts of TAO patients. Moreover, pirfenidone significantly reduced collagen production of orbital fibroblasts. Our results are in agreement with those of previous studies using other fibrosis disease models. In studies using a cyclosporine-induced renal fibrosis model, increases in both TIMP-1 and collagen III mRNA expression were attenuated and reversed by treatment with pirfenidone.\(^\text{31}\) Using a hepatic fibrosis model, Di Sario\(^\text{31}\) reported that pirfenidone administration downregulated TIMP-1 in association with a 70% reduction of collagen deposition. In addition to its antifibrotic effects, which are mediated by reduction of TIMP-1, pirfenidone has been shown to attenuate the expression of heat shock protein 47 in a bleomycin-induced pulmonary fibrosis murine model\(^\text{13}\) and to downregulate intercellular adhesion molecule-1 in cultured human synovial fibroblasts.\(^\text{32}\)

Although the detailed mechanisms by which pirfenidone decreases the levels of TIMP-1 and hydroxyproline remain to be determined, it is unlikely that its inhibitory effects on orbital fibroblasts are the result of cytotoxicity. This conclusion is supported by the results of our MTT assay showing no influence of pirfenidone on cellular viability and the results of previous in vivo and in vitro studies. For example, in a clinical trial of pirfenidone in patients with multiple sclerosis, most participants were able to tolerate this agent at a high dose (2400 mg/d) for 1 year without any significant adverse effects.\(^\text{33}\) Another trial conducted on 73 patients with idiopathic pulmonary fibrosis who were enrolled to receive pirfenidone for 9 months revealed no significant difference in safety profiles between patients receiving pirfenidone and those receiving placebo; both groups reported photosensitivity, stomach discomfort, anorexia, and nausea.\(^\text{34}\) Similar results have been obtained by in vitro studies, which demonstrated that pirfenidone inhibits proliferation, migration, and collagen contraction in human Tenon’s fibroblasts without causing significant cytotoxicity.\(^\text{35}\) Despite these extremely promising indications, the possible adverse effects of pirfenidone should be systematically addressed in advance of clinical application.

In this study, we demonstrated that pirfenidone showed a superior inhibitory effect on both TIMP-1 expression and hydroxyproline accumulation in orbital fibroblasts compared with dexamethasone. Corticosteroids are widely accepted as the first-line drug for treating TAO, particularly when the disease occurs, anorexia, and nausea.\(^\text{34}\) Similar results have been reported to have antifibrotic effects in other types of diseased cells.\(^\text{36,37}\)

In summary, our results provide initial evidence that pirfenidone reduces the levels of TIMP-1 protein and hydroxyproline in orbital fibroblasts of TAO patients. These results indicate that pirfenidone modulates orbital fibroblast reactions in TAO
and thus may be a promising candidate for future use as an antifibrotic agent.

References