NP603, a novel and potent inhibitor of FGFR1 tyrosine kinase, inhibits hepatic stellate cell proliferation and ameliorates hepatic fibrosis in rats

Nan Lin,¹* Si Chen,¹,²* Weidong Pan,¹ Linan Xu,³ Kunpeng Hu,¹ and Ruiyun Xu¹

¹Department of Hepatobiliary Surgery, The Third Affiliated Hospital, Sun Yat-Sen University, GuangZhou; ²Department of Immunology, Anhui Medical University, HeFei; and ³Department of Gynecology and Obstetrics, The First Affiliated Hospital, SunYat-Sen University, GuangZhou, Peoples Republic of China

Submitted 8 November 2010; accepted in final form 28 April 2011

Hepatic stellate cells (HSCs), the primary source of extracellular matrix (ECM) proteins, play a crucial role in liver fibrosis (14, 27). In prolonged liver injury, HSCs undergo a series of autocrine cytokines including transforming growth factor beta (TGF-β) and its main receptor FGFR1 have been shown to promote hepatic stellate cell (HSC) activation and proliferation. However, scant information is available on the anti-fibrogenic activity of FGFR1 inhibitors. The aim of this study was to assess the impact of a selective FGFR1 tyrosine kinase inhibitor NP603 on HSC proliferation and hepatic fibrosis. We demonstrated that rat primary HSCs secreted significant amounts of TGF-β, and its tyrosine phosphorylation of FGFR1 was attenuated by NP603. NP603 inhibited HSC activation by measuring the expression of α-smooth muscle actin (α-SMA) and the production of type I collagen using ELISA. Furthermore, NP603 (25 μM) in vitro strongly suppressed HSC growth induced by TGF-β2 (10 ng/ml) and FCS. This effect correlated with the suppression of extracellular-regulated kinase (ERK) activity and its downstream targets cyclin D1 and p21. In addition, PO NP603 (20 mg·kg⁻¹·day⁻¹) administration significantly decreased hepatic collagen deposition and α-SMA expression in CCl4-treated rats. Collectively, these studies suggest that selective blocking of the FGFR1-mediated pathway could be a promising therapeutic approach for the treatment of hepatic fibrosis.

Fibroblast growth factor 2; smooth muscle actin

* N. Lin and S. Chen contributed equally to this work.

Address for reprint requests and other correspondence: R. Xu, Dept. of Hepatobiliary Surgery, 3rd Affiliated Hospital, Sun Yat-Sen Univ., Guang-Zhou 510630, PR China (e-mail: drxruiyun@gmail.com).

http://www.ajpcell.org 0363-6143/11 Copyright © 2011 the American Physiological Society

First published May 4, 2011; doi:10.1152/ajpcell.00452.2010.

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the experiments. In some of the experiments, cells were serum starved for 24 h in DMEM with 0.2% FBS before treatment.

Cell viability assay. Cell viability analysis was assessed by 3-(4,5-dimethylthiazol)-2,5-diphenyl tetrazolium (MTT) dye absorbance, using a commercially available kit (Roche), and executed according to the manufacturer’s instructions. Primary HSCs were plated at into 96-well plates at an initial density of 5 × 10^3, serum starved in 0.2% FBS-DMEM for 16 h, followed by treatment under serum-free conditions, NP603 (5–100 μM), or DMSO for 48 h. MTT solution (125 μl; 2 mg/ml in PBS) was added to each well and incubated at 37°C for 4 h. Supernatant was removed, and the cells were solubilized in DMSO (250 μl) for 30 min. The optical density was measured at 450 and 690 nm using a 96-well plate reader (Bio-Tek Instruments).

Analysis of HSC proliferation and cell cycle. Cells were seeded at a density of 5 × 10^3 cells per well in 24-well plates, incubated with serum-deprived DMEM for 24 h, and then exposed to the desired experimental conditions. Control cultures received 0.2% FCS or 10% FCS. The proliferative capacity of HSCs was evaluated by 5-bromo-20-deoxyuridine (BrdU) assay according to the manufacturer’s protocol (Amersham, Little Chalfont, UK). Each treatment was given in triplicate. For cell cycle detection, HSCs were harvested, fixed in 70% ethanol for 30 min at −20°C, and suspended in 500 μl PBS containing RNase A for 30 min at 4°C. Fixed cells were stained with propidium iodide (100 mg/l) before fluorescence-activated cell sorting (FACS) analysis as described elsewhere (24).

Western blot analysis. The cell lysates were centrifuged at 16,000 g for 5 min at 4°C, and aliquots containing 30 μg protein were used for Western blot analysis. Protein expression was quantified as previously described (28). Levels of target protein bands were densitometrically determined by using Quantity One 4.6.2 (Bio-Rad). Variations in the density were expressed as arbitrary units (n = 3), and β-actin was generally used as an internal control. Quantification with histograms is shown as the target protein-to-internal control ratio.

Immunoprecipitation. Cells were washed twice with ice-cold PBS and then lysed with lysis buffer for 20 min at 4°C, and the protein content of the supernatant was determined by the bicinchoninic acid method (Pierce, Rockford, IL). Protein (500 μg) was immunoprecipitated at 4°C overnight using the polyclonal FGFR1 antibody (10 μg) and 40 ml of agarose-protein G (Roche Molecular Biochemicals). After being washed twice with lysis buffer, FGFR immune complexes

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Fig. 1. A–C: characterization of isolated rat hepatic stellate cells (HSCs, cultured for 7 days). A: phase-contrast micrographs (with a ×10 objective); B: α-SMA expression (red); C: ultraviolet autofluorescence of retinoid (with a ×20 objective). Light and fluorescence micrographs are representative of 3 independent experiments. D: immunohistochemical staining for fibroblast growth factor-2 receptor (FGFR1) (indicated by arrows, with a ×20 objective) was demonstrated in culture-activated HSCs. E: FGF-2 is secreted by HSCs during in vitro activation. Freshly isolated HSCs were cultured on six-well plates, and supernatants were harvested at the indicated time points. FGF-2 accumulation was evaluated by ELISA. Data represent the means ± SD (n = 3). F: cytotoxicity by NP603 were tested in activated HSCs. HSCs were treated with various concentrations (0–100 μM) of NP603 for 24 h in a serum-free condition. Cytotoxicity was assessed by 3-(4,5-dimethylthiazol)-2,5-diphenyl tetrazolium (MTT) assay. Data represent the means ± SD of 3 independent experiments performed in duplicate. G: effect of an FGFR1-targeted inhibitor on FGFR1 phosphorylation in passed HSCs. HSCs were treated with NP603 for 30 min. Cell lysates were immunoprecipitated for FGFR1. After immunoblotting with a phosphotyrosine-specific antibody (PTyr), the membranes were reprobed to control for FGFR1 protein levels. Representative blots were from 3 independent experiments. *P < 0.05 vs. NP603 0 μM.
were resolved by SDS-PAGE and immunoblotting was performed as described above.

Enzyme-linked immunosorbent assay. Freshly isolated HSCs were incubated in serum-starved DMEM overnight, and the culture medium was replaced with new serum-starved DMEM and supernatant was harvested. FGF-2 concentrations were assessed by ELISA using a commercially available kit (R&D Systems, Minneapolis, MN). For measurement of secreted procollagen type I by HSCs into the culture supernatant was performed with the iScript One-Step RT-PCR Kit with SYBR Green (Invitrogen, Carlsbad, CA). Real-time reverse transcription (RT)-PCR was performed from rat primary HSCs and hepatic tissue using TRIzol Reagent (Bio-Rad) as described previously (9). The housekeeping gene 18S was served as an internal control. The primers used were as follows: rat

- procollagen mRNA: (forward) 5'-gcagctgacttcagggatgt-3' (reverse) 5'-catgttcagctttgtggacct-3'; rat MMP13: (forward) 5'-gaagctctgctgcggttctg-3' (reverse) 5'-ggaa- 3; rat TIMP-1: (forward) 5'-cagctgtagctgtgccccaa-3' (reverse) 5'-ggaagacgctccttcctca-3; rat α-SMA: (forward) 5'-cgatagaacacggcatcat-3' (reverse) 5'-gcatagccctcatagataggca-3; rat 18S: (forward) 5'-gcatagccctcatagataggca-3' (reverse) 5'-gcatagccctcatagataggca-3'; rat MEK1: (forward) 5'-gcatagccctcatagataggca-3' (reverse) 5'-gcatagccctcatagataggca-3';

Plasmids and cell transfection. Hemagglutinin (HA) epitope-tagged WT rat MEK1 cDNA (Upstate, Charlottesville, VA) was subcloned into a pcDNA3.1 expression vector (Invitrogen, CA). Expression constructs for HA-tagged MEK1 have been described (16). The MEK1 expression construct was transiently transfected into cells using Lipofectamine 2000 (Invitrogen, CA). The transfected cells were incubated in fresh growth medium for 24 h. M199 supplemented with 10% FBS and NP603 was added to the cells, and HSCs were collected 24 h later. In these experiments, cells transfected with empty vector served as a control. CCL4-induced rat model of liver fibrosis. The study was performed in adult male Sprague-Dawley rats. The research protocol was approved by the Institutional Ethics Committee. Hepatic fibrosis was induced by peritoneal injection of CCl4 as described previously (18). All fibrotic experimental groups were injected intraperitoneally with 0.2 ml/100 g sterile CCl4 in a 1:1 ratio with olive oil twice weekly. For the in vivo study, one group of five rats was administered CCl4 for 2 wk and then administered 40 mg/kg NP603 (Merck) via oral administration daily for 6 wk together with CCl4 injection. In parallel, another group of five rats received citrate-buffered solution as a vehicle by gavage and also CCl4 by peritoneal injection for 8 wk. After animal euthanasia, specimens of liver tissue were obtained and fixed in 10% neutral buffered formalin for histological analysis. The levels of serum transaminases and alanine aminotransferase (ALT)
were assessed using commercially available assays (Biotron Diagnostics; Hemet, CA).

**Immunohistochemistry and assessment of hepatic collagen content.** Deparaffinized and blocked 5-μm liver sections were incubated with anti-α-SMA antibody (Dako, Carpinteria, CA) at the concentration of 1:100 using the EnVision system (Dako). Diaminobenzidine tetrahydrochloride was used as a peroxidase substrate, and sections were counterstained with hematoxylin and mounted on a coverslip.

Hepatic collagen content was assessed both by Masson’s trichrome staining of liver sections and by hydroxyproline concentration. The positive-stained area was quantified using the morphometry program NIS-Elements Advanced Research (Nikon, Tokyo, Japan). Hepatic hydroxyproline content was determined by colorimetric analysis according to a described method (4).

**Statistical analysis.** Statistical analysis was performed using Microsoft EXCEL software. Unless otherwise specified, the results relative to the number of experiments indicated are expressed as means ± SD. The statistical significance of differences was evaluated using the unpaired Student’s t-test. *P* values <0.05 were considered significant.

**RESULTS**

NP603 attenuates tyrosine phosphorylation of FGFR1 in cultured HSCs. Rat primary HSCs retained a fibroblastic morphology after 7 days cultured with FBS (Fig. 1A). Additionally, expression of α-SMA protein (Fig. 1B) and loss of retinol stores (Fig. 1C), widely accepted as reliable indicators of HSC activation, became apparent in plated HSCs. As shown in Fig. 1, D and E, activated HSCs also express cell surface FGFR1 and secreted significant amounts of biologically active FGF-2, as it was detected at 6 h and continually increased for up to 48 h (Fig. 1E).

Before observing the effect of an FGFR1 tyrosine kinase inhibitor on HSC, we first assessed the cytotoxicity of NP603 in activated HSCs by MTT assay. NP603 at concentrations of

![Fig. 3. NP603 induces cell cycle arrest at G1 in HSCs. A: serum-starved cells were exposed to FGF-2 (10 ng/ml) or FCS (10%) with or without NP603. After 24 h, the distribution of HSCs in the cell cycle was determined by flow cytometry using propidium iodide staining (*n* = 3). Fluorescence-activated cell sorting (FACS) plots are representative of 1 of 3 experiments of identical design. B: an illustration of the FACS data, values are means ± SD of 3 independent experiments. C: effects of NP603 treatment on cyclin D1, p21, and p27 protein expression in HSCs. Whole cell protein extracts were prepared from preconfluent HSCs treated with or without NP603 for 24 h for Western blot analyses. β-Actin was used as an internal control and the results of a representative study are shown (*n* = 3). *P* <0.05 vs. 0 h.]
Fig. 4. Involvement of the ERK pathway in the inhibition of activated HSCs by NP603. 
A: blocking the ERK pathway enhanced the growth-inhibitory effect of NP603 on activated HSCs. Serum-starved HSCs were pretreated with or without PD98059 (10–40 μM) for 30 min before the addition of NP603 (10 μM) to the medium with FBS (10%) for an additional 24 h. Cell proliferation was evaluated by BrdU incorporation into cDNA of cultured HSCs (n = 3). 
B: Western blot analysis of the effects of PD98059 treatment on the regulation of cyclin D1 and p21. Values of BrdU incorporation were presented as fold changes (means ± SD). Representative blots were from 3 independent experiments.*P < 0.05 and #P < 0.01 vs. controls or PD98059 0 μM.

Fig. 5. Overexpression of MEK1 enhances the proliferation of NP603-induced HSC growth. 
A: phosphorylated ERK was overexpressed in HSCs transfected with a cDNA encoding MEK1. HSCs were transiently transfected with a control vector (pcDNA 3.1) or a vector coding for constitutively active MEK1 followed by NP603 (25 μM) treatment for 24 h. Overexpression of MEK1 abrogated the NP603-induced decrease of BrdU incorporation (B) apparently by reversing the NP603-induced changes in cyclin D1 and p21 (C). Representative blots were from three independent experiments. SP < 0.05 vs. controls or pcDNA; **P < 0.05 vs. NP603.
NP603 inhibits HSC activation and FGF-2-induced proliferation in HSCs. The effects of FGFR1 inhibition on the protein expression of α-SMA were investigated in HSCs to measure HSC activation. The results revealed that the expression of α-SMA was almost negligible in quiescent HSCs (day 0) but markedly increased after 7–16 days of culturing, and this increase was impeded by NP603 (Fig. 2A).

To test the FGF-2-regulated proliferative activity of HSCs, FCS was used as a positive control. FGF-2 (10 ng/ml) significantly increased the proliferation of rat HSCs, and this was reduced by pretreatment with NP603, as expected (Fig. 2B).

We next examined the effects of FGFR1 inhibition on the activity of ERK. Western blot analysis clearly indicated FBS-induced activation of ERK, and NP603 dose dependently reduced the level of phosphorylated ERK, which increased significantly following the addition of FGF-2 (Fig. 2C). These results suggest that NP603 might block FGF-2-induced activation of the ERK signaling pathway, and they confirmed the ability of NP603 to interrupt FGF-2 signaling in activated HSCs.

Influence of NP603 on the cell cycle and the activity of cell cycle-signaling proteins in cultured HSCs. Flow cytometric analysis of DNA content was performed to investigate whether NP603 blocks the cell-cycle progression of HSCs. The proportion of cells in either S-phase or G2/M-phase was determined by DNA analysis. NP603 significantly reduced the level of phosphorylated ERK, which increased significantly following the addition of FGF-2 (Fig. 2C). These results suggest that NP603 might block FGF-2-induced activation of the ERK signaling pathway, and they confirmed the ability of NP603 to interrupt FGF-2 signaling in activated HSCs.

Involvement of ERK in the growth-inhibitory effect of NP603 on activated HSCs. To evaluate the role of the ERK signaling pathway in the inhibition of HSC growth by NP603, semiconfluent HSCs were pretreated with or without the specific MEK inhibitor PD98059 (PD) before the addition of NP603. As demonstrated in Fig. 4A, NP603 with PD pretreatment at different doses caused a further significant reduction in cell proliferation via BrdU incorporation assay. Furthermore, it was observed that the treatment of HSCs with PD similarly led to the downregulation of cyclin D1 and the upregulation of p21 in a dose-dependent pattern (Fig. 4B).

Further experiments were aimed at the role of the ERK pathway in the regulation of the cell cycle and the activity of cycle-related proteins by NP603. We transfected cDNA encoding MEK1 into HSCs, and there was a marked increase in the protein expression of p-ERK in MEK1-transfected cells as shown in Fig. 5A. Activation of the MEK/ERK pathway is required for cell cycle progression through regulation of cyclin D1 and p21 in some cell lines (6, 17). We confirmed that the influence of NP603 on the protein expression of cyclin D1 and p21 in HSCs was dramatically abrogated by MEK1 overexpression (Fig. 5C), which lead to a reversal of the NP603-mediated DNA synthesis decrease (Fig. 5B). Thus these results implied that inhibition of activated HSC growth by NP603 might be partially mediated through blockade of ERK activity and its downstream targets cyclin D1 and p21.

Effect of NP603 on collagen type I accumulation in the culture medium and α1(I) procollagen mRNA expression. To examine whether NP603 has an anti-fibrotic effect on HSCs, we assessed the impact of NP603 on the synthesis and mRNA expression of collagen type I. As shown in Fig. 6A, the levels of α1(I) procollagen mRNA expression were inhibited by NP603 compared with the control, with a maximal effect at 50 μM. Pretreatment with NP603 significantly reduced FGF-2-induced synthesis of procollagen type I in cell supernatant, but NP603 did not affect collagen secretion from HSCs incubated in DMEM with 10% FCS (Fig. 6B).

NP603 mitigates CCl4-mediated liver fibrogenesis. Given the above findings, we next asked whether NP603 could
reverse liver fibrogenesis in vivo following CCl₄ administration. Serum ALT concentrations were elevated by CCl₄ challenge, but they decreased after treatment with NP603 (Fig. 7A). Moreover, determination of the hydroxyproline content in the liver revealed a significant decrease in collagen accumulation in CCl₄-treated rats that received NP603 compared with rats challenged with CCl₄ alone (Fig. 7B). This result was further confirmed by the detection of liver fibrosis using Masson’s trichrome stain. Liver tissue morphometry after trichrome staining demonstrated that NP603 (40 mg·kg⁻¹·day⁻¹) treatment significantly decreased hepatic ECM deposition (Fig. 7, C and D). CCl₄ resulted in a marked increase of collagen 1α (I) and MMP13 mRNA, which were suppressed in NP603-treated animals (Fig. 7E). However, tissue inhibitor of metalloproteinase-1 (TIMP1) was not reduced by NP603. Taken together, these data show the therapeutic effect of NP603 on CCl₄-induced hepatocellular damage.

**DISCUSSION**

FGFs stably bind a family of four receptor tyrosine kinases (RTKs) designated the high affinity FGF-receptors FGFRI-FGFR4. Previous studies suggested that several RTKs, which mediate many of the stellate cell’s responses to cytokines, are broadly upregulated during liver injury (2). NP603, similar to the multitargeted RTK inhibitor SU6668 in structure, exhibits potent inhibition of FGF-2-induced proliferation of endothelial cells through FGFR1 binding (19). In this study, we found that NP603 inhibits FGFR1 tyrosine kinase activity by reducing the phosphorylation levels of FGFR1. We did not evaluate the potential effect of NP603 on the other three FGF receptors. Although FGFR inhibitors as promising therapeutic agents exert a direct effect on tumor cell growth and survival (21, 22), their role in the regulation of HSC biology and their fibrogenic potential are largely unknown. Here we found that NP603 displays a strong suppressive effect on HSC activation, proliferation, and ECM production both in vitro and in vivo.

In addition to the growth inhibition of HSCs by NP603, our results demonstrated that ERK1/2 activity was upregulated in response to FGF-2 and that this effect was clearly reduced by NP603. Prior reports indicated that suppressive effects on HSC proliferation are mediated partially through cyclin D1 and the cyclin-dependent kinase inhibitors p27 and p21 (1, 28). Consistent with these data, the impact of NP603 on cyclin D1 and...
This effect is consistent with the in vivo observation showing mRNA and protein production by HSCs induced with FGF-2. We observed that in vitro, NP603 suppressed type I collagen production, indicating the selective inhibition of activated HSCs. These results indicate that the inhibition of HSC proliferation by NP603 of partly involves the ERK signaling pathway and its regulation of cell cycle-related proteins. An- proliferative effect of partly involves the ERK signaling pathway and its regulation of cell cycle-related proteins. Another important finding of this study is the depressive effect of NP603 on α-SMA expression, a marker of HSC activation, both in vitro and in vivo. These results conflict with a study that showed FGF1(−/−) FGF2(−/−) mice exhibited a normal increase in α-SMA and desmin associated with activation and migration of HSCs to damage (31).

In this set of experiments, additional potential anti-fibrotic properties of NP603 were evaluated both in vitro and in vivo animal models. Although serum-free medium did not affect collagen synthesis and secretion in HSCs, we observed that in vitro, NP603 suppressed type I collagen mRNA and protein production by HSCs induced with FGF-2. This effect is consistent with the in vivo observation showing that NP603 PO administration can significantly attenuate CCl4-induced hepatic fibrosis in rats. This observation is supported by the finding that chronic hepatic fibrosis is markedly reduced in FGF1/FGF2-deficient mice (31). Interestingly, NP603 at even higher concentrations (50 μM) had no effect on the synthesis of collagen type I induced by FCS in vitro. Several studies have also suggested that autocrine FGF-2 is the principal cytokine responsible for fibroblast proliferation and plays a central role in the pathogenesis of bone marrow fibrosis and pulmonary fibrosis (3, 8). However, a contribution from other cell types in the liver such as hepatocytes cannot be excluded in the net anti-fibrotic effect of NP603. Some reports suggest that FGF receptor signaling pathways in hepatocytes are crucial regulators of liver regeneration (29). They also showed that blocking secretion of FGF-2 may inhibit survival pathways of hepatocytes and promote liver injury. Therefore, the exact mechanisms of effective anti-fibrotic agents that target the FGF-2 signaling pathway merit further investigation.

In summary, the present study demonstrates that the FGFR1 inhibitor NP603 effectively attenuates phosphorylation of FGFR1 in HSCs and prevents HSC activation. Moreover, it inhibits proliferation of activated HSCs induced by FGF-2, in part by blocking ERK activity and its targets cyclin D1 and p21. Our in vivo experiments demonstrated that NP603 significantly ameliorates CCl4-induced hepatic fibrosis in a rat model. Although further research in this area is needed, our findings position selective FGFR1 inhibitors as potential HSC-targeted drug candidates for the treatment of liver fibrosis.

**REFERENCES**


**GRANTS**

This research is supported by the National Science Foundation for Young Scholars of China (81000674) and Natural Science Foundation of Guangdong Province, China (10451008901004752 and 8151008901000086).

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).


