Modulation of Collagen and MMP-1 Gene Expression in Fibroblasts by the Immunosuppressive Drug Rapamycin

A DIRECT ROLE AS AN ANTIFIBROTIC AGENT?*

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We have examined whether rapamycin, an immunosuppressive drug, may exert part of its antifibrotic activity by directly targeting fibroblast extracellular matrix deposition. Incubation of human lung fibroblast (WI-26) cultures with rapamycin led to dose- and time-dependent reduction in the expression of types I and III collagens, both at the protein and mRNA levels. Rapamycin had no effect on collagen promoter activity but accelerated mRNA decay, indicating post-transcriptional control of collagen gene expression. In contrast, rapamycin significantly enhanced the expression of interstitial collagenase (MMP-1) at the protein and mRNA levels and transcriptionally. We determined that rapamycin efficiently activates AP-1-driven transcription by rapidly inducing c-Jun/AP-1 phosphorylation with activation of the c-Jun N-terminal kinase (JNK) cascade, resulting in enhanced binding of AP-1-DNA complex formation and AP-1-dependent gene transactivation. Conversely, the JNK inhibitor SP600125 inhibited rapamycin-induced MMP-1 gene transactivation and AP-1/DNA interactions. A c-Jun antisense expression vector efficiently prevented rapamycin-induced MMP-1 gene transcription. Pharmacological inhibition of either ERK or p38 MAPK pathways was without effect on rapamycin-induced MMP-1 gene expression. It thus appears that rapamycin may exert direct antifibrotic activities independent from its immunosuppressive action.

Fibrosis is a reactive process involving different pathophysiological events such as attraction of blood-born cells (e.g. leukocytes, platelets, activated lymphocytes), alteration of the microvasculature, and activation of resident mesenchymal cells (fibroblasts, endothelial cells, pericytes) leading to excessive extracellular matrix (ECM) deposition (1–4). Possible explanations for the excessive deposition of collagen observed during the fibrotic process include both an increased biosynthesis or reduced degradation of ECM components, particularly that of fibrillar collagens, by fibroblasts. An accumulation of collagen may originate from accelerated production of collagen resulting from enhanced collagen gene transcription and/or mRNA stabilization in response to soluble factors present in the micro-environment. Alternatively, reduced matrix metalloproteinase (MMP) expression and subsequent inhibition of collagen degradation may also contribute to the fibrotic process (1). Thus, identifying molecules that may either affect collagen production negatively or MMP expression positively is of utmost importance to define novel therapeutic means against fibrosis. In this context, rapamycin (sirolimus), a Streptomyces fungus macrolide antibiotic with potent immunosuppressive properties, is currently used for the prevention of graft rejection in kidney transplant recipients (5–7). Several experimental studies have shown that rapamycin is also effective in preventing liver or pulmonary fibrogenesis in animal models (8–10).

At the cell membrane, rapamycin binds to the immunophilin FK506-binding protein (FKBP12). This rapamycin-FKBP12 complex interacts with the rapamycin binding domain of mTOR, a serine-threonine kinase, and thus inactivates mTOR known to control proteins that regulate mRNA translation initiation and G1 progression in T cells (11). mTOR is a transducer that may be initiated by insulin, growth factors, and amino acids to activate downstream targets and regulate cell growth and proliferation as well as metabolic homeostasis (12, 13). It has been shown that ribosomal protein S6 kinases 1 and 2 (S6K-1 and S6K-2) and the eukaryotic initiation factor 4E-binding protein 4E-BP1 downstream targets of mTOR. Rapamycin induces translational arrest by preventing phosphorylation of S6K-1 and 4E-BP1 by mTOR (14).

Investigations have demonstrated some anti-inflammatory effects of immunosuppressive drugs, including rapamycin, suggesting that they may be considered as antifibrogenic (15, 16). However, the molecular mechanisms underlying the effects of rapamycin on ECM gene expression remain poorly understood. Thus, the aim of this work was to investigate the direct effects of rapamycin on fibrosis-associated genes in fibroblasts and to elucidate the molecular mechanisms associated with the modulation of ECM gene expression by rapamycin. We identify distinct mechanisms by which rapamycin modulates both the expression of fibrillar collagen genes and that of interstitial collagenase/MMP-1.
Rapamycin and Fibrosis-associated Gene Expression

TABLE 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Forward sequence</th>
<th>Reverse sequence</th>
</tr>
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<tbody>
<tr>
<td>COL1A1</td>
<td>5'-GGGGAAGACAGTGAATGCTTA-3'</td>
<td>5'-ACUTGAGGCGGAAATTCTT-3'</td>
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<tr>
<td>COL1A2</td>
<td>5'-TCTGCTACTGGAAGACGCTTA-3'</td>
<td>5'-TCTGAGGCGGAAATTCTT-3'</td>
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<tr>
<td>COL3A1</td>
<td>5'-CCTCTGCTGATGCCCCTTAT-3'</td>
<td>5'-CCACAATGCTGACACACAC-3'</td>
</tr>
<tr>
<td>MMP-1</td>
<td>5'-CCCACAAAGCGTTGACGAT-3'</td>
<td>5'-GGTAGAAGAGATTGTCG-3'</td>
</tr>
<tr>
<td>TIMP-1</td>
<td>5'-GCGACXGCGCGCCG-3'</td>
<td>5'-GGTTGCGGACCTGCGAATG-3'</td>
</tr>
<tr>
<td>GAPDH</td>
<td>5'-GCTTCCTGGCAGGCTCA-3'</td>
<td>5'-ACGTGGAATGCTGACACAC-3'</td>
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EXPERIMENTAL PROCEDURES

Cell Cultures—Human lung fibroblasts (WI-26) were grown in Dulbecco’s modified Eagle’s medium supplemented with 10% heat-inactivated fetal calf serum, 2 mM glutamine, and antibiotics (100 units/ml penicillin, 50 μg/ml streptomycin-G and 0.25 μg/ml Fungizone™) in 5% CO₂ at 37 °C.

Cell Viability Assessment—Equal numbers of WI-26 fibroblasts were cultured in 96-well cell culture clusters and treated with various concentrations of rapamycin for 12, 24, and 48 h. Cell viability was measured using an MTS assay according to the manufacturer’s protocol (Promega, Madison, WI).

Reverse Transcription-PCR Analysis—Total RNA was extracted according to the manufacturer’s instructions using RNeasy mini kit (Qiagen, Hilden, Germany). DNase I treatment (25 units, 15 min) of total RNA was performed to eliminate genomic contamination of the RNA samples. One microgram of total RNA was used for first strand cDNA synthesis using a RT-for-PCR kit (Invitrogen) according to the manufacturer’s instructions. Real-time PCR was performed with an ABI PRISM 7700 instrument (Applied Biosystems, Foster City, CA) using SYBRGreen PCR core reagents (Applied Biosystems). Reaction mixtures were incubated for 2 min at 50 °C followed by 10 min at 95 °C and 40 cycles of 15 s at 95 °C, 45 s at 60 °C, 1.5 min at 95 °C and finally 15 s at 95 °C, 20 s at 63 °C, and 15 s at 95 °C. For each sample, gene expression was corrected against glyceraldehyde-3-phosphate dehydrogenase mRNA level. Primers used for PCR reactions are shown in Table 1.

Transient Cell Transfections and Reporter Assays—Transient cell transfections were performed with jetPEITM according to the manufacturer’s protocol (Polyplus-transfection, Illkirch, France). pRSV-β-galactosidase was cotransfected in every experiment to monitor transfection efficiency. CAT activity was measured using [14C]chloramphenicol as substrate followed by thin layer chromatography and quantitation with a PhosphorImager (Amersham Biosciences). Luciferase activity was determined with a commercial assay kit (Promega). For high transfection efficiency of the pRSV-AS-c-jun expression vector, cells were electroporated with a Nucleofector™ (Amaxa GmbH, Köln, Germany) according to the manufacturer’s protocol. Transfection efficiency was estimated to be 80% by fluorescence-activated cell sorter analysis of a cotransfected green, fluorescent protein expression vector (data not shown).

Plasmid Constructs—−3500COL1A2/CAT (gift from Francesco Ramirez, Mount Sinai School of Medicine, New York, NY), −2300COL1A1/CAT (gift from John Varga, Northwestern University Feinberg School of Medicine, Chicago, IL), −400COL3A1/CAT (gift from Benoit de Crombrugghe, University of Texas M. D. Anderson Cancer Center, Houston, Texas), −517MMP-1-lux and corresponding AP-1 mutant

FIGURE 1. Rapamycin decreases type I collagen protein synthesis. A, serum-starved fibroblast cultures were treated with various concentrations of rapamycin (1, 0.1, or 0.01 μg/ml) for 24 h or 48 h, as indicated. After incubations, type I collagen production was detected by Western blot analysis of whole cell lysates (upper panel). Specificity of the modulation was confirmed with an anti-collagen antibody. The ratio of type I collagen to actin is plotted from the values of densitometric analysis of Western blots of four representative experiments. B, fibroblast cultures were treated with various concentrations of rapamycin (10 μg/ml, 1 μg/ml (△), or 0.1 μg/ml (X)) or not (○) for 6, 24, or 48 h, after which cell viability was measured using an MTS assay. Values are the mean of three independent experiments, each performed with triplicate samples.
Rapamycin and Fibrosis-associated Gene Expression

constructs. Twelve hours after transfections, rapamycin (1 μg/ml) for 1, 24, or 48 h. After incubations, COL1A1 (A), COL1A2 (B), and COL3A1 (C) mRNA steady-state levels were determined by quantitative RT-PCR. Bars indicate mean ± S.D. of at least three independent experiments performed, each with duplicate samples. D–F, serum-starved fibroblast cultures were transfected with −2300COL1A1/CAT (D), −3500COL1A2/CAT (E), and −400COL3A1/CAT (F) constructs. Twelve hours after transfections, rapamycin (1 μg/ml) was added and incubations continued for another 48 h. Autoradiograms shown are from a representative experiment, each for the three experiments being performed with duplicate samples.

FIGURE 2. Rapamycin decreases COL1A1, COL1A2, and COL3A1 mRNA steady-state levels without repressing the activity of the corresponding promoters. A–C, serum-starved subconfluent fibroblast cultures were treated with rapamycin (1 μg/ml) for 12, 24, or 48 h. After incubations, COL1A1 (A), COL1A2 (B), and COL3A1 (C) mRNA steady-state levels were determined by quantitative RT-PCR. Bars indicate mean ± S.D. of at least three independent experiments performed, each with duplicate samples. D–F, serum-starved fibroblast cultures were transfected with −2300COL1A1/CAT (D), −3500COL1A2/CAT (E), and −400COL3A1/CAT (F) constructs. Twelve hours after transfections, rapamycin (1 μg/ml) was added and incubations continued for another 48 h. Autoradiograms shown are from a representative experiment, each for the three experiments being performed with duplicate samples.

Rapamycin Inhibits Type I Collagen Production in Human Lung Fibroblasts—We first wanted to determine whether rapamycin had a direct effect on collagen production by fibroblasts. To address this point, WI-26 human lung fibroblast cultures were incubated with various concentrations of rapamycin, and type I collagen production was measured by Western blot analysis. As shown in Fig. 1A, total type I collagen production was reduced by rapamycin in a time- and dose-dependent manner. Specifically, a decrease of 10 and 45% with a rapamycin concentration of 0.1 μg/ml and a decrease of 37 and 60% with a concentration of 1 μg/ml were respectively observed after 24 h (upper panel) and 48 h (lower panel) of treatment. Interestingly, even the smallest concentration of rapamycin (0.01 μg/ml) had a significant inhibitory activity after 48 h of incubation, suppressing collagen production by as much as 30%.

To ensure that the inhibition of collagen production was not because of a cytotoxic effect of rapamycin, WI-26 fibroblasts were incubated for 6, 24, and 48 h with rapamycin concentrations ranging from 0.1 to 10 μg/ml, and cell viability was determined at various time points. As shown in Fig. 1B, no significant cell mortality was observed at any of the concentrations tested over a 48-h period.

Rapamycin Decreases COL1A1, COL1A2, and COL3A1 mRNA Steady-state Levels by Decreasing mRNA Stability and without Affecting Gene Transcription—To determine whether the reduction of fibrillar collagen production by rapamycin occurred via modulation of the corresponding genes, we first measured COL1A1, COL1A2, and COL3A1 mRNA steady-state levels following rapamycin treatment by quantitative RT-PCR. As shown in Fig. 2, rapamycin at a concentration of 1 μg/ml decreased COL1A1 (Fig. 2A), COL1A2 (Fig. 2B), and COL3A1 R&D Systems (Minneapolis, MN) according to the manufacturer’s instructions.
Rapamycin and Fibrosis-associated Gene Expression

(Fig. 2C) mRNA levels in a time-dependent manner, the extent of inhibition reaching 48, 56, and 70%, respectively, after 48 h. To determine whether the effect of rapamycin on COL1A1, COL1A2, and COL3A1 expression takes place at the transcriptional level, transient cell transfections were performed with the collagen promoter/gene reporter constructs −2300COL1A1/CAT, −3500COL1A2/CAT, and −400COL3A1/CAT. As shown in Fig. 2, COL1A1 (Fig. 2D), COL1A2 (Fig. 2E), and COL3A1 (Fig. 2F), gene promoter activities were not altered by rapamycin, suggesting that the effect of rapamycin observed at the mRNA levels (see above) does not occur via transcriptional regulation of the corresponding genes.

We thus investigated whether rapamycin may affect the stability of COL1A1, COL1A2, and COL3A1 mRNAs. For this purpose, fibroblasts were incubated with the transcription inhibitor actinomycin D for one hour prior to addition of rapamycin. mRNA decay was then measured in the absence or presence of rapamycin. As shown in Fig. 3, treatment with rapamycin accelerated COL1A1 (Fig. 3A), COL1A2 (Fig. 3B), and COL3A1 (Fig. 3C) mRNA decay, thus significantly reducing their half-lives. COL1A1, COL1A2, and COL3A1 mRNA half-lives were estimated to be about 16 h in the absence of rapamycin and dropped to around or slightly below 6 h with rapamycin. Together, these results indicate that rapamycin inhibits fibroblast collagen production via post-transcriptional mechanisms that affect COL1A1, COL1A2 and COL3A1 mRNAs stability.

Rapamycin Increases MMP-1 Gene Expression and Protein Synthesis—We first wanted to determine whether rapamycin had direct effect on MMP-1 synthesis. To address this point, MMP-1 protein production was measured using MMP-1 immunoassay approach. As shown in Fig. 4A, rapamycin treatment of WI-26 fibroblasts led to increase in MMP-1 protein production, up to 2.2- and 4.5-fold, respectively, after 48 and 72 h at the concentration of 1 μg/ml.

We next determined whether rapamycin modulates MMP-1 and/or TIMP-1 gene expression. To address this point, the effects of rapamycin on MMP-1 and TIMP-1 mRNA steady-state levels were studied by quantitative RT-PCR. Rapamycin treatment of WI-26 fibroblasts led to a time- and dose-dependent increase in MMP-1 mRNA levels, up to 3.5-fold after 48 h at the concentration of 1 μg/ml (Fig. 4, B and C). On the other hand, TIMP-1 gene expression remained unaltered over the same incubation period (not shown).

c-Jun Mediates Rapamycin-driven MMP-1 Gene Transcription—Most MMP genes exhibit promoter regions that are characterized by a functional AP-1 binding site around position −70 relative to the transcription initiation site that is critical for transcriptional regulation by a variety of stimuli, including cytokines (22). The effect of rapamycin on MMP-1 promoter transactivation was examined in parallel transient cell transfection experiments using either a wild-type MMP-1 reporter construct −517MMP-1-lux or an AP-1 mutant not able to bind AP-1 proteins (23). Results shown in Fig. 5A demonstrate that the effect of rapamycin on MMP-1 gene expression was transcriptional, as rapamycin induced a 2.5-fold transactivation of the MMP-1 promoter. Furthermore, we determined that the integrity of MMP-1 promoter AP-1 binding site is necessary for transactivation by rapamycin that fails to transactivate the AP-1 mutant construct.
Next, the effect of rapamycin on AP-1-driven transcription was examined in transient cell transfection experiments with an artificial, multimerized AP-1 reporter construct, pAP1-TA-lux. As shown in Fig. 5B, rapamycin enhanced pAP1-TA-lux activity 2.6-fold above control levels, attesting for the capacity of rapamycin to transactivate AP-1-dependent promoters.

To determine whether rapamycin modulates AP-1/DNA interactions, EMSA experiments were carried out with a radio-labeled consensus AP-1 oligonucleotide as a probe. As shown in Fig. 5C and D, EMSA experiments were performed using a consensus AP-1 oligonucleotide as a probe, together with nuclear extracts from control (C, lane 1; D, lanes 1 and 2) and rapamycin-treated (1 μg/ml for 30, 60, and 120 min, respectively (C, lanes 2, 3, and 4) and for 30 min (D, lanes 3 and 4)) fibroblast cultures. Supershift assay was carried out with an anti-c-Jun antibody (D, lanes 2 and 4).

Next, the effect of rapamycin on AP-1-driven transcription was examined in transient cell transfection experiments with an artificial, multimerized AP-1 reporter construct, pAP1-TA-lux. As shown in Fig. 5B, rapamycin enhanced pAP1-TA-lux activity 2.6-fold above control levels, attesting for the capacity of rapamycin to transactivate AP-1-dependent promoters.

To determine whether rapamycin modulates AP-1/DNA interactions, EMSA experiments were carried out with a radio-labeled consensus AP-1 oligonucleotide as a probe. As shown in Fig. 5C, AP-1-DNA complexes were detected with nuclear supernatates were collected, and MMP-1 protein levels were estimated by immunoassay. Bars indicate mean ± S.D. of two independent experiments performed, each with six replicate samples. B and C, serum-starved subconfluent fibroblast cultures were treated with rapamycin (1 μg/ml) for various times (12, 24, and 48 h) or with various concentrations of rapamycin (0.001, 0.01, 0.1, and 1 μg/ml) for 48 h (C). MMP-1 mRNA levels were estimated by quantitative RT-PCR. Bars indicate mean ± S.D. of two independent experiments performed, each with duplicate samples.
extracts from unstimulated control WI-26 fibroblast cultures (lane 1). Rapamycin induced a 1.5-, 4.2-, and 6.5-fold elevation of AP-1-DNA binding complexes after 30 min, 1 h, and 2 h of treatment, respectively (lanes 2–4).

To identify whether c-Jun, the main component of AP-1 complexes (24), was present in the protein-DNA complex identified with the AP-1 probe, supershift experiments were performed with an anti-c-Jun antibody. Results presented in Fig. 5D indicate that the retarded band obtained with nuclear extracts from control extracts (lane 1) and elevated in nuclear extracts from rapamycin-treated fibroblasts (lane 3) is significantly reduced by the anti-c-Jun antibody (lanes 2 and 4), attesting for the presence of c-Jun in the complexes.

To verify the implication of c-Jun in the activation of MMP-1 gene expression by rapamycin, an antisense c-jun expression vector, which specifically targets c-jun expression and no other Jun family member (19, 25), was transfected into WI-26 fibroblasts prior to rapamycin treatment. Inhibition of c-Jun expression in antisense-transfected cells, treated or not with rapamycin, was verified by Western blotting (Fig. 6, inset). Quantitative RT-PCR analysis of MMP-1 mRNA steady-state levels indicated a 95% reduction in rapamycin effect on MMP-1 gene expression when cells received the antisense c-jun vector prior to incubation with rapamycin (Fig. 6). Taken together, these results demonstrate the critical role played by c-Jun in mediating rapamycin-dependent MMP-1 gene expression at the transcriptional level.

JNK Mediates Rapamycin-driven AP-1 Transcriptional Activity and Subsequent Modulation of MMP-1 Gene Expression—MAPKs act as signal transducers originating from numerous extracellular stimuli. MAPKs of the c-Jun N-terminal kinase family are critical determinants of the strength of AP-1-dependent transcription, as JNK phosphorylation of Jun protein members confers them maximal transcriptional potential (26, 27). Likewise, p38 and ERK contribute to potentiate Fos-mediated transcription (27). At present, little is known about their possible role downstream of rapamycin.

Given the effects of rapamycin on AP-1-dependent transcription and the implication of the MMP-1 promoter AP-1 binding site in mediating rapamycin effect on MMP-1 gene expression, we investigated the capacity of rapamycin to induce
c-Jun phosphorylation and JNK activation. As shown in Fig. 7A, rapamycin addition to WI-26 fibroblast cultures induced a rapid and prolonged phosphorylation of c-Jun on Ser-63, detectable as early as 15 min following stimulation and persisting at least 2 h. Likewise, rapamycin efficiently and rapidly induced JNK phosphorylation with a very similar kinetic (Fig. 7B). On the other hand, rapamycin had no effect on p38 MAPK activation (Fig. 7C), whereas ERK phosphorylation was stimulated as early as 15 min, peaked at 30 min, and slowly came down to basal level over the 2-h period following rapamycin addition (Fig. 7D).

To assess the role played by MAPKs in mediating rapamycin-driven induction of MMP-1 gene expression, we investigated the ability of specific inhibitors of the JNK, p38, and ERK pathways to alter rapamycin-driven MMP-1 gene expression. Results shown in Fig. 8A indicated that pretreatment of fibroblast cultures with the specific JNK inhibitor SP600125 totally inhibited the effect of rapamycin on MMP-1 mRNA level. In contrast, the ERK and p38 inhibitors PD98059 and SB203580 failed to suppress rapamycin effect.

Next, in a similar experimental approach, the JNK inhibitor SP600125 prevented rapamycin-driven AP-1 transcriptional activity, as measured in transient cell transfection experiments with pAP-1-TA-lux (Fig. 8B), whereas the ERK and p38 inhibitors PD98059 and SB203580 did not. Finally, EMSA experiments with a radiolabeled consensus AP-1 oligonucleotide demonstrated that a 1-h pretreatment with SP600125 abolished rapamycin-driven elevation of AP-1-DNA complexes (Fig. 8C, lane 4 versus lane 2). Together, these experiments demonstrate the critical and specific role played by the JNK pathway in mediating rapamycin effects on both AP-1-dependent transcription and MMP-1 gene expression in human lung fibroblasts.

**DISCUSSION**

In this report, we provide evidence that the immunosuppressive drug rapamycin, an inhibitor of mTOR, may exert direct antifibrotic activities both by down-regulating type I and type III collagen synthesis and by up-regulating MMP-1 synthesis. In accordance with a previous report showing that a mTOR-specific interfering RNA and a kinase dead mTOR decrease type I collagen steady-state mRNA levels (28), we demonstrate that rapamycin inhibits COL1A1, COL1A2, and COL3A1 gene expression by decreasing their mRNA stability.

Many reports demonstrated that collagen deposition is precisely controlled by collagen mRNA stabilization. For example, Krupsky et al. (29) demonstrated that COL1A1 mRNA stability is reduced by amino acid deprivation in lung fibroblasts. Furthermore, retinoic acid and prostaglandin E2, which decrease the uptake of amino acids transported, decrease the steady-state levels of COL1A1 mRNA by decreasing its stability (30, 31). In the context of mTOR inhibition, Peng et al. (32) have shown that deprivation of amino acids induces a cellular stress response similar to that elicited by rapamycin, supporting the conjecture that mTOR acts as a nutritional sensor, and that pharmacological inhibition of mTOR by rapamycin, in some respects, mimics the signal induced by amino acid deprivation. Interestingly, it was recently demonstrated that FK506 signifi-

**FIGURE 8. Critical role for JNK in mediating rapamycin effects on MMP-1 gene expression.** A, serum-starved subconfluent fibroblast cultures were treated with rapamycin (1 μg/ml) for 48 h in presence or absence of SP600125 (10 μM), PD98059 (10 μM), or SB203580 (10 μM) as indicated. After incubations, MMP-1 mRNA levels were detected by quantitative RT-PCR. Bars indicate mean ± S.D. of three independent experiments performed with duplicate samples. B, serum-starved fibroblast cultures were transfected with pAP-1-lux construct. 6 h after, cells are treated with rapamycin (1 μg/ml, 24 h) in presence or absence of SP600125 (10 μM), PD98059 (10 μM), or SB203580 (10 μM) as indicated. Bars indicate mean ± S.D. of three independent experiments performed, each with duplicate samples. C, EMSA experiment was performed using the AP-1-specific oligonucleotide as a probe, together with nuclear extracts from control (lanes 1 and 3) and rapamycin-treated (1 μg/ml for 60 min; lanes 2 and 4) fibroblast cultures in presence of SP600125 (10 μM; lanes 3 and 4) or in absence of this inhibitor (lanes 1 and 2).
Rapamycin and Fibrosis-associated Gene Expression
cantly reduces the basal expression of the human COL1A2 mRNA levels in scleroderma fibroblasts by reducing their sta-

bility (33). Thus, our results suggest that rapamycin may be an interesting candidate drug for the treatment of fibrotic condi-
tions because an increase in collagen mRNA stability contrib-
utes to elevated collagen levels in scleroderma fibroblasts (34).

We also demonstrated that rapamycin increases MMP-1 gene expression. We provide definitive evidence for a direct role for the JNK/c-Jun pathway in mediating rapamycin effect at the transcriptional level through enhanced AP-1-dependent

tunities because an increase in collagen mRNA stability contrib-
utes to elevated collagen levels in scleroderma fibroblasts (34).

With regard to JNK function in the context of antifibrotic

properties, our findings are complementary to our recent works indicating that JNK, which is critical in conferring transcrip-
tional activity to Jun proteins, is also instrumental in allowing

these proteins to interfere with Smad-dependent gene tran-
scription downstream of TGF-β, a major player in the develop-
ment of tissue fibrosis (2, 3). We specifically demonstrated that

activators of the JNK pathway, such as tumor necrosis factor-α (36–38) and 5-FU (39), antagonize TGF-β-induced collagen
gene expression by preventing Smad/DNA interaction and related gene expression (2, 3). Thus, it may be speculated that

JNK activation by rapamycin may have a similar inhibiting effect on TGF-β-driven collagen production. In conclusion, we

have identified that rapamycin may exert direct antifibrotic activities by molecular mechanisms that affect both matrix pro-
duction and degradation by fibroblasts.

REFERENCES