Relaxin attenuates silica-induced pulmonary fibrosis by regulating collagen type I and MMP-2

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Abstract

Silicosis is one of the most prevalent occupational lung diseases, but the pathogenic mechanisms of silicosis are largely unknown and an effective treatment is not yet available. In this study, we investigated the potential effects of relaxin (RLX) on fibrosis by an in vitro model involving silica-induced and macrophage-mediated pulmonary fibroblasts. Following pre-treatment with DQ12 quartz, the culture supernatant of human monocytic THP-1 cells was added to human fetal lung fibroblast MRC-5 cells with or without RLX. DQ12 significantly induced an increase of TGFβ1 mRNA in THP-1 cells, coinciding with elevated TGF-β1 protein excretion in the supernatant, but RLX had no effect on DQ12-stimulated TGF-β1 secretion in THP-1 cells. Furthermore, RLX inhibited the proliferation of MRC-5 cells, and reduced the mRNA level and protein secretion of collagen type I, whereas it increased the mRNA level and protein activity of MMP-2 in MRC-5 cells treated with THP-1 cell culture supernatant. Our data suggest that RLX may inhibit TGF-β1-mediated fibrosis during the process of silicosis, providing evidence for the protective effect of RLX on silica-induced pulmonary fibrosis.

Keywords:
Silicosis
Relaxin
Macrophage
Fibroblast
Collagen type I
Matrix metallopeptidase 2

1. Introduction

Silicosis is a fibrotic pulmonary disease characterized by fibroblast proliferation and excessive collagen deposition, and is initiated by inhalation of crystalline silica dusts [1,2]. The pathogenic mechanisms of silicosis remain to be determined and an effective treatment is not available.

Accumulating evidence demonstrates that macrophages and fibroblasts play key roles in silica-induced fibrotic reactions [3]. Activation of macrophages following the ingestion of silica particles releases fibrogenic and inflammatory cytokines including transforming growth factor-1 (TGF-β1), which in turn stimulates pulmonary fibroblasts to produce collagen. This ultimately leads to the development of fibrosis [2–7]. Paradoxically, fibroblasts also secrete matrix-metalloproteinases (MMPs) to induce ECM degradation. Therefore, an imbalance between pro-fibrotic factors and anti-fibrotic factors might lead to excessive collagen deposition, tissue re-modeling and finally pulmonary fibrosis [8,9]. It has been proposed that a constant production of fibrotic factors by macrophages contributes to the progression of silica-induced lung fibrotic lesions by recruiting and stimulating the proliferation of fibroblasts [10]. It is thus intriguing to postulate that blocking the stimulatory effect of macrophages on fibroblasts after silica exposure, might provide an effective strategy to prevent silica-induced lung fibrosis.

Relaxin (RLX) was first identified in 1926 and subsequently regarded as a hormone that could re-model ECM in the female reproductive tract, in order to facilitate parturition [11]. Recent studies indicated that RLX plays an important role in connective tissue homeostasis [12], and exogenous RLX demonstrated anti-fibrotic effects in non-reproductive tissues including the heart [13], kidney [14], dermis [15] and lung [16]. In vitro, RLX decreased matrix accumulation by inhibiting the secretion and/or deposition of collagen while stimulating the expression of MMPs, and reduced the TGF-β1-induced secretion of collagen and/or fibronectin in human lung fibroblasts [16]. In vivo, either RLX or RLX receptor gene-knockout mice demonstrated an increase in interstitial collagen in the lung [17,18]. Furthermore, RLX inhibited the bleomycin-induced fibrosis in a murine model [16], which shares some histopathological features of silica-induced pulmonary fibrosis [19]. These data suggest that RLX is a potential therapeutic drug for silica-induced pulmonary fibrosis.

In order to explore the protective effect of RLX on silica-induced pulmonary fibrosis, we established an in vitro model using macrophages (human monocytic THP-1 cells) and fibroblasts (human fetal lung fibroblast MRC-5 cells) to examine the effect of RLX on TGF-β1 synthesis in silica-induced THP-1 cells. We also assessed the effect on cell proliferation, collagen synthesis, and expression of MMP-2 in silica-induced and macrophage-mediated pulmonary fibroblasts.
2. Materials and methods

2.1. Cell and reagents

Human mononcytic cell line (THP-1) and human fetal fibroblast cell line (MRC-5) were obtained from the Institute of Cell Research, Chinese Academy of Science (Shanghai, China), and cultured in MEM supplemented with 10% fetal bovine serum (FBS) at 37 °C in a humidified atmosphere of 5% CO₂. Dörendrup quartz, ground product no.12 (DQ12), with a mean diameter of 0.96 μm, was heated for 16 h at 220 °C to remove possible endotoxin contamination [20]. DQ12 was suspended in MEM (2 mg/mL) and sterilized. Phorbol myristate acetate (PMA), obtained from Sigma Chemical, was dissolved in DMSO (1 mg/mL) and stored in the dark at −20 °C. Relaxin (RLX, recombinant human gene-2 relaxin), purchased from R&D Systems (Minneapolis, MN, USA), was dissolved in phosphate-buffered saline (PBS) to make a solution of 1 μg/mL.

2.2. PMA-primed THP-1 cells

THP-1 cells (5.0 × 10⁵/mL) were maintained in MEM complete medium at 5% CO₂ and 37 °C, and incubated with 10 ng/mL PMA for 48 h to facilitate differentiation into macrophages (differentiated THP-1 cells, which are hereafter referred to as diff THP-1) [21]. Following replacement with serum-free MEM, diff THP-1 were divided into 4 different treatment groups: MEM only (control), DQ12 (200 μg/10⁶ cells) only, RLX (100 ng/mL) only and DQ12 plus RLX (100 ng/mL). The different cell types were incubated for 1, 3, 6 and 12 h [22]. After incubating with DQ12, the culture supernatants (CS) from diff THP-1 cells (THP-1 CS) were harvested, sterilized with 0.22-μm millipore filter, and stored in −80 °C for further use. Diff THP-1 were collected and prepared for total RNA extraction. The level of TGF-β1 in THP-1 CS was measured using human TGF-β1 ELISA kit (Westang, Shanghai, China) following the manufacturer’s protocol.

2.3. Proliferation of MRC-5 cells by conditioned medium

Proliferation of MRC-5 cells was determined using WST-8 dye (Beyotime Inst Biotech, China) according to the manufacturer’s instructions. Briefly, MRC-5 cells were cultured in 96-well plates (4 × 10³ cells/well) for 24 h, and then the culture mediums were switched to MEM supplemented with 0.2% lactalbumin hydrolysate for another 48 h. Next, cells were divided into 4 different treatment groups including MEM only (control), THP-1 CS only, RLX only and THP-1 CS plus RLX. The RLX concentration was 1, 10 and 100 ng/mL, respectively. After 48 h, MRC-5 cells were photographed with an Olympus microscope at ×400 magnification. 10 μL WST-8 dye was then added to each well, cells were incubated at 37 °C for 2 h and the absorbance was determined at 450 nm using a microplate reader (Synergy 2, Bio-Tek Instrument, Inc., Winooski, VT, USA).

2.4. Measurement of MMP-2 activity and collagen type I concentration in culture supernatant from MRC-5 cells

MMP-2 activity was analyzed by zymography as previously described [23]. Firstly, MRC-5 cells were cultured in 6-well plates (1.2 × 10⁵ cells/well) for 24 h, and then the cells were incubated in MEM supplemented with 0.2% lactalbumin hydrolysate for another 24 h. Lastly, the cells were divided into 4 different treatment groups including MEM only (control), THP-1 CS only, RLX only and THP-1 CS plus RLX. After 48 h, supernatants of MRC-5 cells were harvested for determination of collagen type I concentration and MMP-2 activity. Samples were subjected to electrophoresis on a 4% acrylamide stacking gel/7% acrylamide separating gel containing 1 mg/mL gelatin in the presence of sodium dodecyl sulfate (SDS) under non-reducing conditions. After electrophoresis, gels were washed twice in 2.5% Triton X-100 and then incubated at 37 °C overnight in substrate buffer (50 mM Tris, 10 mM CaCl₂, 200 mM NaCl, 0.05% polyethylene glycol monododecyl ether, pH 8.0). The gels were stained with Coomassie Blue R250, and de-stained in a solution of 40% methanol and 10% acetic acid. MMP-2 activity appeared as bright bands against a blue background. Density of the band was graphed to estimate the degree of MMP-2 induction by RLX and its biphasic dose-dependency. Results were expressed as arbitrary units of relative intensity. MRC-5 cells were collected and prepared for total RNA extraction. The collagen type I concentration in culture supernatant from MRC-5 cells was measured using the Human Collagen type I ELISA kit (Westang, Shanghai, China).

2.5. Isolation of RNA and quantitative real-time polymerase chain reaction

Total cellular RNA was isolated and evaluated as previously described [24]. Briefly, total RNA was extracted from the cells using TRIzol reagent (Invitrogen, Carlsbad, CA, USA) according to the manufacturer’s instructions. First strand cDNA was synthesized from 2 μg of total RNA using the RevertAid First Strand cDNA Synthesis Kit (Fermentas, MD, USA) in a total volume of 20 μL. The primers of the genes (Table 1) used in the experiments were synthesized by TaKaRa Biotechnology (Dalian, China). QRT-PCR analysis was carried out on the ABI Prism 7900 Sequence Detection System (Applied Biosystem, CA, USA) using SYBR Green qPCR SuperMix-UDG kit (Invitrogen, Beijing, China) according to the manufacturer’s instructions. Each reaction was run in triplicate with appropriate negative controls. The conditions for PCR were: initial denaturation step at 50 °C for 2 min followed by 40 cycles of 15 s at 95 °C for denaturation, 30 s at 60 °C for annealing and 15 s at 72 °C for extension. The melting curve analysis was performed for identification of the gene. All samples were normalized to the β-actin values and data were analyzed by the 2−ΔΔCT method [25].

2.6. Statistical analysis

All the experiments were independently performed at least three times, and related measurements were expressed as mean ± standard deviation. All data were processed with SPSS 12.0 for Windows (SPSS Inc., Chicago, IL, USA). Statistical significance was carried out by one-way analysis of variance (ANOVA) followed by Dunnett’s t test. A value of P < 0.05 was considered statistically significant.

3. Results

3.1. DQ12 increases the expression of TGF-β1 in the differentiated THP-1 cells

THP-1 cells were floating and round in appearance before PMA treatment. After incubation with PMA (10 ng/mL) for 48 h, more than 90% of THP-1 cells became adherent to the culture dish (data not shown). To analyze the effect of DQ12 quartz particles and RLX on the expression of TGF-β1 in the differentiated THP-1 cells, TGFβ1 mRNA in diff THP-1 and protein levels of TGF-β1 in the supernatant was determined by QRT-PCR and ELISA, respectively. TGFβ1 mRNA in the diff THP-1 significantly increased after treatment with DQ12 for 12 h (P < 0.05).

Table 1

<table>
<thead>
<tr>
<th>Gene</th>
<th>Primer sequence</th>
<th>Product size (bp)</th>
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<tbody>
<tr>
<td>TGFβ1</td>
<td>AAGAAGGAAAAATATTGTTTCA</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>CCAACTGCTATGACTGGA</td>
<td></td>
</tr>
<tr>
<td>COL1A1</td>
<td>TGGCTGAGAAGGTTTCA</td>
<td>134</td>
</tr>
<tr>
<td>MMP2</td>
<td>CTCTGGACGCGGTTTCA</td>
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</tr>
<tr>
<td>ACTB</td>
<td>TGCGACGGCTGTTCTCACA</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>CTGAAATATGCTGCCCTGACCA</td>
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as compared with control, whereas there was no significant change between control and RLX-treated diff THP-1 (Fig. 1A). Consistent with this result, TGF-β1 protein in the supernatant of diff THP-1 progressively elevated following the treatment of DQ12, reaching peak value of 120 pg/mL at 12 h (P < 0.01), while there was no significant change between DQ12 and DQ12 plus RLX (Fig. 1B). These data demonstrated that DQ12 quartz particles induced the expression of TGF-β1 in diff THP-1 but RLX had no effect on DQ12-stimulated TGF-β1 secretion in diff THP-1.

3.2. RLX abolishes the enhanced proliferation of MRC-5 cells induced by THP-1 CS

We found that only the supernatant of diff THP-1 exposed to DQ12 for 12 h could increase the proliferation of MRC-5 cells (data not shown). We thus used the supernatant of 12 hour-stimulated diff THP-1 (THP-1 CS) to study the effect of RLX on the stimulating activity induced by DQ12. In comparison to control, the phenotype of fibroblasts changed significantly after treatment with THP-1 CS. Quiescent fibroblasts were activated and transformed to myofibroblasts, but RLX had no effect on these (Fig. 2A). Consistent with this result, the number of MRC-5 cells significantly increased after treatment with THP-1 CS (P < 0.01), whereas, there was no significant change between control and RLX-treated MRC-5 cells. The number of MRC-5 cells treated with THP-1 CS plus RLX significantly decreased compared to those treated with THP-1 CS (P < 0.01) (Fig. 2B). These data indicated that RLX abolished the enhanced proliferation of MRC-5 cells induced by THP-1 CS.

3.3. Effect of RLX on the transcription of COL1A1 and MMP2 in MRC-5 cells

We next investigated the effect of RLX on the transcription of fibrosis-related genes COL1A1 and MMP2 in MRC-5 cells by QRT-PCR. In comparison to control, COL1A1 mRNA of MRC-5 cells was significantly increased by THP-1 CS (P < 0.05). In contrast, there was a statistically significant decrease of COL1A1 mRNA in MRC-5 cells after treatment with THP-1 CS plus RLX as compared to THP-1 CS alone (Fig. 3). In addition, the transcription of MMP2 was elevated in a dose-dependent manner in MRC-5 cells exposed to RLX compared with control. Furthermore, the expression of MMP2 in MRC-5 cells was increased after treatment with THP-1 CS (P < 0.01) plus RLX as compared with THP-1 CS alone (Fig. 3). These results demonstrated that RLX decreased the THP-1 CS-induced expression of COL1A1 while increasing the MMP2 mRNA irrespective of the effect of THP-1 CS in MRC-5 cells.

3.4. RLX enhances the MMP-2 activity in MRC-5 cells

Then we assessed the effect of RLX on the MMP-2 activity in the supernatant of MRC-5 cells by zymography and found that THP-1 CS induced a statistically significant increase in the activity of MMP-2 (P < 0.05) (Fig. 4). Moreover, treatment with THP-1 CS plus RLX led to a significant increase in the MMP-2 activity in the supernatant of MRC-5 cells compared to THP-1 CS alone (P < 0.01). These data suggested that RLX together with THP-1 CS had a synergistic effect on the activity of MMP-2 in MRC-5 cells.

3.5. RLX decreases THP-1 CS-induced secretion of collagen type I in MRC-5 cells

Finally, we tested the effect of RLX on the secretion of collagen type-I in the supernatant of MRC-5 cells by ELISA and discovered that THP-1 CS increased collagen type I in culture supernatant of MRC-5 cells (P < 0.05), whereas RLX did not change collagen type I level. By contrast,
the level of collagen type I in the culture supernatant of MRC-5 cells was statistically significantly decreased after treatment with THP-1 CS plus RLX as compared to THP-1 CS alone (P < 0.01) (Fig. 5). These data indicated that RLX decreased THP-1 CS-induced secretion of collagen type I without altering the basal level of collagen type I in MRC-5 cells.

4. Discussion

In this study, we established an in vitro model of pulmonary fibrosis using THP-1 and MRC-5 cells and evaluated RLX on the profibrotic effects induced by silica. We found that RLX had no effect on DQ12-stimulated TGF-β1 secretion in THP-1, but RLX abolished the
THP-1 CS-stimulated proliferation of MRC-5 cell, collagen type I expression and secretion. Moreover, RLX increased the expression and activity of MMP-2 in the MRC-5 cells treated with THP-1 CS. Our results suggest that RLX targets fibroblasts cells and has an anti-fibrotic effect on silica-induced pulmonary fibrosis.

Differentiated THP-1 cells demonstrate some biological and morphological characteristics of human alveolar macrophages, such as cytokine production, therefore they represent a useful model to investigate the function of macrophages in silica-induced pulmonary tissue damage [26,27]. The human fetal lung fibroblast MRC-5 cell line is widely used to study the function and regulation of fibroblasts in fibrogenic response of the lung [28,29]. The inhibition of cell migration, proliferation and phenotypic differentiation of MRC-5 cells was used as an indication of the potential of an agent for therapy of pulmonary fibrosis [30]. Furthermore, activated macrophages increase the release of cytokines and growth factors, which induce the proliferation of fibroblasts and collagen synthesis, ultimately leading to silica-induced pulmonary fibrosis [31]. To explore RLX’s potential for therapy of silica-induced pulmonary fibrosis, we developed an in vitro model of silica-induced pulmonary fibrosis by using culture supernatants of silica-treated, PMA-primed THP-1 cells to induce the profibrotic activity of MRC-5 cells, which mimic the interaction between macrophages and fibroblasts in vivo during silica-induced pulmonary fibrosis.

Our results demonstrated that RLX is a potential anti-fibrotic agent for silica-induced pulmonary fibrosis. RLX inhibited the proliferation, expression and secretion of collagen type I in MRC-5 fibroblasts, suggesting that RLX may balance the proliferation of fibroblast and the expression of connective tissue component, which are the key contributors to silica-induced interstitial lung fibrosis. In addition, RLX increased the mRNA levels and secretion of MMP-2 protein in MRC-5 fibroblasts. Up-regulation of MMPs is an important regulatory step in the degradation of collagen [8,32]. Taken together, these data suggest that RLX might prevent the silica-induced pulmonary fibrosis via inhibiting fibroblast proliferation, collagen synthesis, and MMP-2 activation.

Macrophage activation and subsequent endogenous TGF-β1 up-regulation and secretion are essential steps in initiating a fibrotic response [33]. Our data showed an increase of mRNA expression and protein secretion of TGF-β1 in diff THP-1 after treatment with DQ12. In agreement, several reports demonstrated that TGF-β1 expression [34] or its ability to promote fibroblast proliferation and matrix synthesis [15,35–37] was abrogated by RLX. Different from the previous in vitro experiments, THP-1 CS used in this study displayed both pro- and anti-fibrotic cytokines, which was induced by DQ12 in alveolar macrophages.

In conclusion, our study demonstrated that RLX could antagonize the profibrosis of silica-induced, macrophage-mediated pulmonary fibroblasts, and suggested that RLX may exert its anti-fibrotic actions by inducing MMP-2 activation in pulmonary fibroblasts. Since no effective therapy for silicosis is currently available, and RLX has been demonstrated to successfully reverse the pathological collagen accumulation in an in vivo model of fibrosis induced by surgically, chemically or genetically modified means [12], the protective effect of RLX on silica-induced pulmonary fibrosis suggests a promising further development of RLX as a therapeutic agent for the treatment of silica-induced pulmonary fibrosis.

**Fig. 4.** Effect of RLX on MMP-2 activity in MRC-5 cells. The MRC-5 cells were treated with RLX (1, 10 and 100 ng/mL) for 48 h in the absence or presence of THP-1 CS. MEM was used as control. Culture supernatants were resolved on gelatin zymogram for detection of MMP-2 activity. Data are expressed as the mean ± SD of triplicate cultures. *P < 0.05 and **P < 0.01 compared with control and ***P < 0.01 compared with THP-1 CS.

**Fig. 5.** Effect of RLX on the secretion of collagen type I in MRC-5 cells. The MRC-5 cells were treated with RLX (1, 10 and 100 ng/mL) for 48 h in the absence or presence of THP-1 CS. MEM was used as control. Collagen type I in culture supernatant was measured by ELISA. Data are expressed as the mean ± SD of triplicate cultures. **P < 0.01 compared with control and ***P < 0.01 compared with THP-1 CS.
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References