Long non-coding RNA H19 deficiency ameliorates bleomycin-induced pulmonary inflammation and fibrosis

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Abstract

Background: The poor understanding of pathogenesis in idiopathic pulmonary fibrosis (IPF) impaired development of effective therapeutic strategies. The aim of the current study is to investigate the roles of long non-coding RNA H19 (lncRNA H19) in the pulmonary inflammation and fibrosis of IPF.

Methods: Bleomycin was used to induce pulmonary inflammation and fibrosis in mice. The mRNAs and proteins expression in lung tissues was determined by quantitative real-time polymerase chain reaction (qRT-PCR) and western blot. H19 knockout (H19−/−) mice were generated by CRISPR/Cas9.

Results: The expression of H19 mRNA was up-regulated in fibrotic lungs patients with IPF as well as in lungs tissues that obtained from bleomycin-treated mice. H19−/− mice suppressed bleomycin-mediated pulmonary inflammation and inhibited the Il6/Stat3 signaling. H19 deficiency ameliorated bleomycin-induced pulmonary fibrosis and repressed the activation of TGF-β/Smad and S1pr2/Sphk2 in the lungs of bleomycin-treated mice.

Conclusions: Our data suggests that H19 is a profibrotic lncRNA and a potential therapeutic target for IPF.

Keywords: Pulmonary fibrosis, lncRNA H19, Smad, S1pr2

Background

Idiopathic pulmonary fibrosis (IPF) is a progressive and highly lethal pulmonary fibrotic lung disease with poor treatment and unknown etiology, which rises significantly with age and higher in men [1–4]. Patients with IPF present similar characteristics to the usual interstitial pneumonia (UIP), including extracellular matrix deposition, alveolar architectural disruption, and subpleural honeycombing [5]. The patients with IPF usually have clinical experiences from cough to respiratory insufficiency and have a median survival time of 3 to 5 years after diagnosis [1, 4]. Unfortunately, there are currently no effective therapies capable of stabilizing or improving lung function for patients with IPF.

Long non-coding RNAs (lncRNAs) are defined as non-protein encoding RNA molecules that are more than 200 bp long in length [6]. lncRNAs have been shown to play important roles in different physiological activities, such as gene imprinting, cell proliferation, differentiation, apoptosis, migration, and immune responses [7, 8]. Recent studies have shown that aberrant expression of lncRNAs are associated with a number of human diseases, including cardiovascular, neurodegenerative, lung diseases, tumors and infections [9–15]. The lncRNA H19 is an imprinted and maternally expressed gene that plays a vital role in the controlling the cell proliferation and differentiation [16–18]. The others and our recent studies both indicate that hepatic H19 level is correlated with the severity of cholestatic injury and liver fibrosis in mice [19, 20]. Furthermore, H19 was also related to progression of...
lung cancer and lung fibrosis [21–24]. Although these studies suggest a causal link among H19 and pulmonary injury, it remains unknown whether and to what extent H19 is involved in the regulation of pulmonary fibrosis in vivo. In present study, we identified H19 as an up-regulated IncRNA in the lungs of pulmonary fibrosis. We further determined the functional roles and underlying mechanisms of H19 in pulmonary fibrosis, which suggested H19 acts as a profibrotic IncRNA in the lungs.

**Materials and methods**

**Materials**

Hydroxyproline Assay Kit (Cat. No. MAK008-1KT, Sigma-Aldrich, St. Louis, MO), PowerUp SYBR-Green Master Mix kit (Cat. No. A25742) and a High Capacity cDNA Reverse Transcription kit (Cat. No. 4368814) were obtained from Applied Biosystems (Foster City, CA). NuPAGE 10% Bis–Tris gel (Cat. No. NP0301BOX, Invitrogen, Carlsbad, CA). Bleomycin (Cat. No. HY-17565, MedChemExpress, LLC, NJ), The antibodies used in this study were showed in Additional file 1: Table S1.

**A mouse model of bleomycin-induced pulmonary fibrosis**

H19−/− (H19 ΔExon1-5) mice were generated by CRISPR/Cas9-mediated genome engineering in C57BL/6 mice as our previously described [20]. The animal procedures were approved by the Shanghai Jiaotong University School of Medicine affiliated Xin Hua hospital Animal Care and Use Committee (XHEC-F-2020-008). The mice (about 8 weeks old) were divided into four groups: wild type (Wt) sham (n = 8–12), H19−/− sham (n = 6–10), wild type (Wt) treated with bleomycin (BLM) (n = 8–12) and H19−/− treated with bleomycin (BLM) (n = 8–12). For bleomycin administration, mice were anaesthetized with 2% isoflurane, and then instilled intratracheally with bleomycin (3.5 mg/kg body weight) in 100 μl PBS, as previously described [25, 26]. After 4 weeks, the lung tissues were collected for RNA, protein, collagen content analyses and histological analysis. The degree of fibrosis was quantitated using an Ashcroft score in a blinded manner according to the described method [27].

**Fluorescence in situ hybridization (FISH)**

H19 FISH in mouse lung tissue was performed using a commercially available RNAscope Multiplex Fluorescent Reagent Kit v2 (Advanced Cell Diagnostics, Newark, CA) and RNAscope© Probe-Mm-H19 (#423751, Advanced Cell Diagnostics, Newark, CA) according to the manufacturer’s instruction. Fluorescent staining targeting Sftpc protein was performed followed H19 FISH.

**Quantitative real-time polymerase chain reaction (qRT-PCR)**

Total RNA was extracted from left lung of mice using the RNAsiy kit (Qiagen, Hilden, Germany) according to the protocol of the manufacture and 2 μg of total RNA was used to synthesize the 1st cDNA using a High Capacity cDNA Reverse Transcription kit (Applied Biosystems, Foster City, CA). The real-time PCR reactions were performed on the ViiA 7 Real-Time PCR System (Applied Biosystems, Foster City, CA) using PowerUp SYBR-Green Master Mix kit (Applied Biosystems, Foster City, CA). All samples were assayed in triplicate, and data were normalized to endogenous control Hprt1. Relative RNA expression levels were calculated using the ΔΔCt method. The primers are listed in Additional file 1: Table S2.

**Western blotting**

A total 30 mg left lung tissues was homogenized in 300 μl RIPA buffer (Invitrogen, Carlsbad, CA) supplemented with a protease inhibitor cocktail (Servewbio, Wuhan, China). After determining the protein concentration, the equal amounts of protein were separated on NuPAGE 10% Bis–Tris gels (Invitrogen, Carlsbad, CA) and transferred onto polyvinylidene difluoride (PVDF) membranes. After blocking in 5% nonfat milk at room temperature for 60 min, membranes were incubated with the primary antibodies overnight at 4 °C. The membranes were washed three times for 30 min with TBST (containing 0.1% Tween-20), and then incubated with secondary antibodies. After final washes with TBST, the signals were detected using ECL chemiluminescence reagent Kit (Pierce, Rockford, IL, USA). The primary antibodies performed in this study as showed in Additional file 1: Table S1.

**Histology and immunofluorescence (IF)**

The right lung tissues were immediately fixed in 10% neutral buffered formalin for 24 h and go through dehydration, clearing and paraffin embedding. Sections were mounted on positively charged slides after cutting at 4 μm thick, baked at 65 °C for 1 h and then stored at room temperature (RT) for later use. Fibrosis was performed using mason’s trichrome (Genmed Scientifics, Wilmington, DE, USA) and Sirius red stain (Servicebio, Wuhan, China) following the protocols of manufactures. For immunofluorescence (IF) assay, the slides were incubated with xylol and descending concentrations of ethanol. Endogenous peroxidases were blocked by using 0.3% H2O2 for 10 min at RT. After antigen retrieval, blocking was performed using 5% bovine serum albumin for...
30 min at RT. The antibodies used here were listed on Additional file 1: Table S1.

Hydroxyproline assay
The amount of collagen in the lung tissues was determined by a Hydroxyproline Assay Kit according to the manufacturer’s protocol (Cat. No. MAK008-1KT, Sigma-Aldrich, St. Louis, MO). Briefly, about 10 mg lung tissues were homogenized in 100 μl water with 100 μl concentrated hydrochloric acid (HCl, 12 M) and hydrolyzed at 120 °C for 3 h. Transfer 20 μl of supernatant at 60 °C until completely desiccated. Chloramine T/Oxidation Buffer Mixture was added at room temperature for 5 min, followed by the addition of Diluted DMAB Reagent and incubation at 60 °C for 90 min. Measure the absorbance of samples and standards at 560 nm, and hydroxyproline content was expressed as μg per mg lung tissue.

Statistical analysis
All data were expressed as mean ± SD (standard deviation). For comparisons of different groups, statistical significance was determined by Student’s t-test or ANOVA analysis. P-value less than 0.05 was considered statistically significant.

Results
H19 is up-regulated in fibrotic lungs
Analysis of publicly available datasets showed that lncRNA H19 expression was more highly expressed in lung tissue from patients with IPF compared to normal lung tissue, but there was no significant difference between IPF patients and other interstitial lung diseases (ILD) (Fig. 1a) [28, 29]. Fibrotic genes, including ACTA2, COLIA2 and MMP7, increasingly expressed in lung tissue from patients with IPF compared to lung tissue from patients with other ILD and to normal lung tissue (Fig. 1a) [28, 29]. In addition to, H19 expression increased upon bleomycin-induced lung fibrosis in rats. H19 expression peaked after about 2 weeks of bleomycin-treatment, and then H19 levels returned to an amount comparable to controls (Fig. 1b) [30]. In current study, Fluorescent in situ hybridization (FISH) assay showed that H19 expression increased in lungs of bleomycin-treated mice (2 weeks) and located at alveolar epithelium and capillaries (Fig. 1c). Furthermore, immunofluorescent staining of surfactant protein C (Sftpc), a marker for type 2 epithelial cells (AEC2s), indicated that H19 was also expressed and up-regulated in AEC2s following bleomycin-treatment (Fig. 1c). The qRT-PCR assay confirmed that H19 increasingly expressed in the lungs of mice with bleomycin (BLM) treatment (Fig. 1d, e).

H19 deficiency represses bleomycin-induced lung inflammatory response
H19 knock out (H19−/−) mice here were used to elucidate the roles of H19 in bleomycin-induced pulmonary inflammation and fibrosis. After 4-week BLM-treatment, immunofluorescence (IF) staining showed the H19−/− BLM mice had less CD45+ cells accumulated in the lungs than that in lungs of Wt BLM mice (Fig. 2a). RT-PCR analysis showed that CD11b and Ccr2 genes expression was reduced significantly in lungs of H19−/− mice when compared to that of Wt mice (Fig. 2b). The inflammatory markers, including F4/80, CD11b, Ccl20, Il1b and Ccr2 increased in Wt BLM mice compared to WT sham mice, but decreased in H19−/− BLM mice (Fig. 2b). Western blot results indicated that protein expression levels of Il6 and p-Stat3 were decreased in lungs of H19−/− BLM mice relative to the Wt BLM (Fig. 2c, d).

H19 knockout ameliorates bleomycin-induced pulmonary fibrosis
As shown in Fig. 3, histopathological analysis firstly showed reduced fibrosis in the H19−/− BLM mice (Fig. 3a, b). The haematoxylin–eosin (H&E) staining and Collagen I immunofluorescence (IF) staining showed the fibrosis increased in Wt BLM mice compared to the Wt sham mice, but not in lungs of H19−/− BLM mice (Fig. 3a). The Masson’s Trichrome staining and Sirius red staining further indicated that 4-week BLM significantly induced lung fibrosis in WT mice, but had much less impact in H19−/− mice (Fig. 3a). Consistently, quantitation of lung fibrosis in a blinded manner revealed the Ashcroft score decreased significantly in H19−/− BLM mice when compared to Wt BLM mice (Fig. 3b). Furthermore, the pulmonary hydroxyproline levels were significantly increased in Wt BLM mice, but not in H19−/− BLM mice (Fig. 3c). At molecular level, H19−/− mice had decreased...
expression of Tgfβ1 and Acta2 mRNA in the lungs in relation to Wt animals (Fig. 3d). The mRNA levels of Tgfβ1, Acta2 and Col1a1 (Fig. 3d) and protein expression of Col1a1 (Fig. 3e, f) reduced in H19−/− BLM mice compared to the Wt BLM mice.

H19 depletion attenuated the pathways of TGF-β/Smad and S1pr1/Sphk2 in fibrotic lungs

TGF-β/Smad signaling is the key regulating pathway in fibrogenesis [31]. In this study, we showed that the TGF-β mRNA level and protein levels of p-Smad2 and p-Smad3 were increased in the Wt BLM mice, compared with Wt sham mice, while these proteins reduced in H19−/− BLM mice (Fig. 4a, b). Our previous study had reported that S1pr2 and SphK2 played an important role in promoting liver fibrosis [20]. As shown in Fig. 4, Western blot results indicated that protein expression levels of S1pr2 and SphK2 were increased in lungs of Wt BLM mice compared to Wt sham mice, but decreased in lungs of H19−/− BLM (Fig. 4c, d).

H19 deficiency decreased AEC2s proliferation in lungs of bleomycin-treated mice

In the lung sections from the H19−/− BLM mice, immunofluorescence results showed that expression of Sftpc was decreased relative to that of the Wt BLM mice (Fig. 5a). Additionally, the number of Ki67-positive cells was also reduced in the H19−/− BLM mice compared to the Wt BLM mice (Fig. 5a and Additional file 1: Figure S1). Consistently, western blot results indicated that protein expression levels of Sftpc reduced in the H19−/− BLM mice compared to the Wt BLM mice (Fig. 5b, c). In addition to, the proteins of p-Egfr decreased in lungs of H19−/− BLM mice compared to the Wt BLM mice (Fig. 5b, c).

Discussion

Presently, the poor understanding in the pathogenesis of IPF has resulted in a lack of effective therapies. In the current study, we showed that the IncRNA H19 was up-regulated in the fibrotic lungs of IPF patients and bleomycin-treated mice. Functionally, H19 deficiency reduced pulmonary inflammation and inhibiting Il6/Stat3 signaling. H19 knockout ameliorated bleomycin-induced pulmonary fibrosis through attenuating the TGF-β/Smad and S1pr2/Sphk2 pathways. Moreover, we also indicated that H19 expressed in the type 2 epithelial cells (AEC2s) and contributed to the proliferation of AEC2s.

H19 is an imprinted and maternally expressed transcript, which is one of the few well-characterized IncRNA [32, 33]. Aberrant expression of H19 has been related to a variety of human diseases [34–38]. Using a public datasets, it showed that IPF patients had higher levels of H19 mRNA in lungs when compared to the control subjects. Similarly, H19 mRNA also increased in a model of bleomycin-induced pulmonary fibrosis. In current study, we also showed that H19 expression increased in lungs of bleomycin-treated mice and located at alveolar epithelium and capillaries. From the above findings, we hypothesize that H19 may play an important role in the pathogenesis of IPF. To realize our aim of this study, we firstly generated a H19 deficiency mouse (H19−/−).

Pulmonary inflammation and fibrosis caused by repetitive lung injury underlies the IPF. In vivo studies, we showed that H19−/− mice could attenuate bleomycin-induced pulmonary inflammation. During the bleomycin-induced mice, the CD11b and Ccr2 mRNA expression increased the lung of wild type mice, but not in that of H19−/− mice. Recently, Li et al., reported that H19 significantly induced the expression and secretion of chemokine (C–C motif) ligand 2 (CCL-2) that could accumulate the monocytes from circulation into livers [39]. It thus suggests that H19 contributes to the pulmonary inflammation may via attracting the CD11b monocytes into the lung after injuries. The signaling studies presented here revealed that Il6/Stat3 was reduced in the bleomycin damaged lungs of H19−/− mice. In the injured lung, Stat3 rapidly activated and increased the production of the proinflammatory molecules IL1β, IL6, TNF-α, iNOS and CCL2 [40–43]. It thus propose that H19−/− mice reduced bleomycin-induced pulmonary inflammation may through attenuating the Il6/Stat3 signaling. In vivo studies further revealed H19 deficiency significantly reduced bleomycin-induced pulmonary fibrosis. TGF-β/smad signaling is one of the key pathways responsible for pulmonary fibrosis [31, 44–46]. The current study indicated that H19−/− mice attenuated the TGF-β/smad signaling in bleomycin damaged lungs by reducing the expression of Tgfβ1 mRNA and activated the Smad2/3 protein.
**Fig. 3** H19 deficiency ameliorated bleomycin-induced pulmonary fibrosis in mice. **a** Representative images of hematoxylin–eosin (H&E) staining, Masson’s trichrome staining, Sirius red staining and collagen I immunofluorescence staining of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. **b** Ashcroft score for Sham Wt (n = 10), Sham H19−/− (n = 7), Wt BLM (n = 9) and H19−/− BLM (n = 9) mice. **c** Quantifying collagen content with hydroxyproline assay in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. Each group, n = 6–8. **d** Real-time PCR analysis for Tgfb1, Col1a1 and Acta2 in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. Each group, n = 8–10. **e** Western blot analysis for collagen type I in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. **f** Quantification of the panel (e).

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**Fig. 4** H19 depletion altered the TGF-β/Smads and S1pr2/Sphk2 pathways in lungs of bleomycin-induced mice. **a** Western blot analysis for Smad1/5, Smad2, Smad3, Samd4 and their phosphorylated forms in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. **b** Quantification of the panel (a). **c** Western blot analysis for S1pr2 and Sphk2 in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. **d** Quantification of the panel (c).
Fig. 5 H19 depletion reduced cell proliferation in lungs of bleomycin-induced mice. a Representative images of co-staining for Sftpc and Ki67 in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice. b Western blot analysis for Sftpc, p-Egfr, Egfr, Lin28 and β-actin in the lungs of Sham Wt, Sham H19−/−, Wt BLM and H19−/− BLM mice.
Consistently, in vitro study revealed that H19 can target miR-140 and regulate the TGF-β/Smad3 pathway [24]. Moreover, H19 could enhance TGF-β signaling in both hepatic stellate cells and hepatocytes and facilitate liver fibrosis [47]. H19 has been reported to accelerate TGF-β1-induced tenogenic differentiation in vitro and promoted tendon healing in a mouse tendon defect model [48]. Sphingosine-1-phosphate and its receptor S1pr2 have been shown to promote lung fibrosis [49–53]. Our previous study also showed that H19 could activate the S1pr2/SphK2 signalling pathway in the cholestatic liver. The current study indicated that S1pr2/SphK2 signalling was activated in the bleomycin-treated lungs, but these effects were attenuated by H19 knockout. We thus propose that H19 contribute to lung fibrosis of IPF may via regulating both TGF-β/smad and S1pr2/SphK2 signalling. Epidermal growth factor receptor (EGFR) is a major driver of lung adenocarcinoma, which is essential to lung cancer cell proliferation [54]. The present study also showed H19 deficiency repressed EGFR activating and suppressed the ACE2s proliferation.

Conclusion
In summary, we demonstrated that the H19 is a potential therapeutic target for IPF patients. We propose two novel mechanisms underlying H19 activity in the pathogenesis of IPF. H19 knockout inhibits pulmonary inflammation by attenuating the Il6/Stat3 signaling. H19 acts as a profibrotic IncRNA in the lung of IPF via regulating the TGFβ/Smad and S1pr2/Sphk2.

Supplementary information
Supplementary information accompanies this paper at https://doi.org/10.1186/s12931-020-01534-6.

Additional file 1: Table S1. Antibody information. Table S2. Sequences of primers. Figure S1. Quantification of the Fig. 5a.

Abbreviations
IPF: Idiopathic pulmonary fibrosis; IncRNA: Long non-coding RNA; H19; UIP: Usual interstitial pneumonia; RT-PCR: Real-time polymerase chain reaction; IF: Immunofluorescence; H&E: Hematoxylin–eosin; EGFR: Epidermal growth factor receptor; TGF-β receptor: Transforming growth factor-β, S1pr2: Sphingosine-1-phosphate receptor 2; Sphk2: Sphingosine kinase 2; ACTA2: Alpha 2 smooth muscle actin; COL1A2: Collagen type I alpha 2; MMP7: Matrix metalloproteinase 7.

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Authors’ contributions
XW and YX developed study concept and design, acquisition of data, analysis and interpretation of data. XW, XT, JD and YL performed and analyzed most of the experiments. XW and YX wrote the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
Original data can be requested from corresponding author.

Ethics approval and consent to participate
The animal experiments were approved by the Shanghai Jiao Tong University School of Medicine affiliated Xin Hua hospital Animal Care and Use Committee (XHEC-F-2020-008).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing financial interest.

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