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Idiopathic pulmonary fibrosis (IPF) is a deadly disease with limited therapies. Tissue fibrosis is associated with type 2 immune response, although the causal contribution of immune cells is not defined. The AP-1 transcription factor Fra-2 is upregulated in IPF lung sections, and Fra-2 transgenic mice (Fra-2Tg) exhibit spontaneous lung fibrosis. Here, we show that bleomycin-induced lung fibrosis is attenuated upon myeloid inactivation of Fra-2 and aggravated in Fra-2B bone marrow chimeras. Type VI collagen (ColVI), a Fra-2 transcriptional target, is upregulated in 3 lung fibrosis models, and macrophages promote myofibroblast activation in vitro in a ColVI- and Fra-2–dependent manner. Fra-2 or ColVI inactivation does not affect macrophage recruitment and alternative activation, suggesting that Fra-2/ColVI specifically controls the paracrine profibrotic activity of macrophages. Importantly, ColVI-KO mice and ColVI-KO bone marrow chimeras are protected from bleomycin-induced lung fibrosis. Therapeutic administration of a Fra-2/AP-1 inhibitor reduces ColVI expression and ameliorates fibrosis in Fra-2Tg mice and in the bleomycin model. Finally, Fra-2 and ColVI positively correlate in IPF patient samples and colocalize in lung macrophages. Therefore, the Fra-2/ColVI profibrotic axis is a promising biomarker and therapeutic target for lung fibrosis and possibly other fibrotic diseases.

Introduction

Fibrosis is the result of an abnormal healing process that can occur in every solid organ where hyperactive fibroblasts, called myofibroblasts, characterized by the expression of α-SMA, produce an excess of extracellular matrix (ECM). This accumulation of ECM ultimately alters organ structure and function (1, 2), and no treatment can halt or reverse fibrosis progression. Organ fibrosis is a leading cause of death worldwide and an important focus of research over the past years (3, 4). One dramatic example is idiopathic pulmonary fibrosis (IPF), a common manifestation of interstitial lung diseases (ILDs). IPF progression is very fast, with a median postdiagnosis survival of 2.5 years and a 20% to 30% 5-year survival rate (5). The current treatment options for IPF, including lung transplantation and the recently approved nintedanib and pirfenidone (6, 7), are ineffective (8–10). A common feature of wound healing and fibrosis is the long-lasting presence of alternatively activated macrophages (AAMs), which participate in the resolution of inflammation and in the fibroblast-myofibroblast conversion (4, 11–14).

Macrophages also contribute to ECM remodeling by producing matrix-related proteins, such as matrix-degrading enzymes and fibronectin (15–17). AAMs have an important role in chronic diseases as well as cancer and are therapeutically relevant in preclinical models (18, 19). IL-4 and IL-13 are the main inducers of alternative macrophage activation (20). These cytokines can lead to fibrosis by direct and indirect effects on fibroblasts together with or independently of the canonical profibrotic TGF-β1 (21, 22).

AP-1 proteins form dimers to activate or repress gene transcription in a context-dependent manner and are involved in causation of a variety of chronic diseases, from psoriasis to cancer, acting by regulating cellular processes, such as proliferation, differentiation, and inflammation (23, 24). Genetically engineered mice expressing the AP-1 transcription factor Fra-2, encoded by Fosl2, develop spontaneous systemic fibrosis (25). The accumulation of ECM is particularly prominent in the lungs of Fra-2 transgenic (Fra-2Tg) mice and causes premature death. Furthermore, fibrotic Fra-2Tg lungs display high IL-4 expression with eosinophilic and macrophage infiltration and vascular remodelling (25).

Using several preclinical models for lung fibrosis, we sought to define the cellular and molecular determinants of lung fibrosis...
and evaluate the therapeutic relevance of targeting AP-1 or any of these determinants. We show that Fra-2–expressing macrophages are important contributors to lung fibrosis, secreting fibroblast-activating factors, such as type VI collagen (ColVI). Importantly, while macrophage alternative activation and Th2 immunity are overall not affected, reduced bleomycin-induced lung fibrosis is observed in mice with broad or myeloid-specific Fra-2/AP-1 inactivation as well as in ColVI KO mice and ColVI BM chimeras.

Results

AAMs are prominent in lungs of Fra-2Tg mice. Immunohistological analysis of prefibrotic (before structural changes; at 6 weeks old) and fibrotic (17 weeks) Fra-2Tg lungs revealed that Fra-2 protein was upregulated as well as in ColVI KO mice and ColVI BM chimeras.

Molecular changes, mRNA expression of ECM proteins, such as periostin, Col3a1, or fibroblast-related type I and III collagens (Col1a2 and Col3a1), or fibroblast-specific protein-1 (S100a4), were increased (Figure 1A). Consistent with the early occurrence of fibrosis-associated molecular changes, mRNA expression of ECM proteins, such as type I and III collagens (Col1a2 and Col3a1), or fibroblast-related genes, such as fibroblast-specific protein-1 (S100a4), was increased in prefibrotic (6 weeks) Fra-2Tg lungs (Supplemental Figure 1, A and B; supplemental material available online with this article; https://doi.org/10.1172/JCI125366DS1). In Fra-2Tg lung protein extracts, periostin, α-SMA, and osteopontin were increased at as early as 5, 9, and 12 weeks of age, respectively (Supplemental Figure 1C). Global gene expression analyses (RNA-Seq) and gene set enrichment analysis (GSEA) revealed positive correlation between prefibrotic Fra-2Tg lungs and published gene signatures related to ECM and collagen, but also with IL-4 response and alternative activation of macrophages (Figure 1B). TGF-β pathway activation was not apparent from RNA-Seq/GSEA (not shown) or immunoblot analyses (Supplemental Figure 1D), consistent with published studies (28). GSEA also confirmed Fra-1/2 pathway activation in Fra-2Tg lungs (Supplemental Figure 1E), and deconvolution into cell-specific subprofiles revealed enrichment in myeloid signatures, such as neutrophils, eosinophils, dendritic cells, and macrophages (Supplemental Figure 1F). Importantly, a significant increase in genes characteristic of AAMs, such as Ccl17, Ccl22, Chi3l3, Chi3l4, Mrc1, and Arg1, encoding for the chemokines Ccl17 and Ccl22, the chitinases Ym1 and Ym2, the mannose receptor 1/CD206, and arginase 1, respectively, was apparent in Fra-2Tg lungs (Supplemental Figure 1, G and H). In contrast, markers of classically activated macrophages (CAM), such as Cdc86, Irf5, Il1b, and Il12a, were overall not consistently changed (Supplemental Figure 1, G and H). Macrophage activation is defined in vivo and in vitro by the organ source, the activator molecule, and the expression of a consensus collection of markers (29). According to this definition, gene expression profiling suggests that M(IL-4) macrophages are enriched in the lungs of young prefibrotic Fra-2Tg mice.

Fra-2–expressing myeloid cell populations were next analyzed by flow cytometry using the GFP reporter included in the Fra-2 transgene and by cell-surface marker expression (Supplemental Figure 1, I and J). In prefibrotic and fibrotic Fra-2Tg lungs, Fra-2 transgene expression was detected in all myeloid cell populations in proportions ranging from 70% to 90% and also in epithelial, endothelial, and mesenchymal cells (Figure 1C). A dramatic loss of resident alveolar macrophages was observed in Fra-2Tg mouse lungs at 12 weeks, while macrophages and eosinophils significantly increased (Figure 1D).

Flow cytometry analyses of macrophages revealed an upregulation of AAM marker CD206 (encoded by Mrc1) on Siglec-F–CD11b+ alveolar macrophages in the lungs of 12-week-old Fra-2Tg mice. Although surface CD206 remained low on conventional, non-alveolar (Siglec-F-CD11b+CD45+ CD140a+) macrophages (Figure 1E), gene expression analyses of a panel of CAM and AAM markers in sorted lung macrophages revealed strong upregulation of Mrc1 transcription together with other AAM-associated genes (Figure 1F), consistent with alternative activation. Furthermore, the AAM marker Ym1 was coexpressed with Fra-2 in Csf-1r–positive macrophages in Fra-2Tg lung sections, and a progressive increase in Ym1-positive and Fra-2/Ym1 double-positive cells was observed over time (Figure 1G and Supplemental Figure 1K). Overall, these data indicate that AAMs, likely with a M(IL-4) phenotype, could be a relevant early contributor to lung fibrosis in the Fra-2Tg mouse model.

Fra-2 is upregulated during bleomycin-induced experimental fibrosis in mice. Intratracheal administration of the antineoplastic drug bleomycin is a well-established ILD paradigm, with fibrotic lesions developing from 1 week and progressing during 21 days, followed by slow repair or progression to death (30). The lung function decline due to tissue stiffening can be followed by longitudinal plethysmography in bleomycin-treated mice, as lung resistance (LR) increases over time, while dynamic compliance (DC) decreases, resulting in a higher LR/DC ratio (Supplemental Figure 2A).

In WT mice, Fra-2 protein was detected in lung sections as early as 10 days after bleomycin instillation (Figure 2A and Supplemental Figure 2B). mRNA expression in the lung and the bron-
 expression increase was also detected in BALF cells and lung tissue (Supplemental Figure 2D). BALF contained high numbers of macrophages after bleomycin, while neutrophils and lymphocytes were barely detected (Supplemental Figure 2E). Fra-2 protein was detected in alveolar lavage fluid (BALF) was evaluated over time (Supplemental Figure 2C). Fra-2 mRNA expression peaked in BALF and lung at 3 and 10 days after bleomycin, respectively, and preceded collagen accumulation (Figure 2B). TGF-β1 and AAM marker gene expression increase was also detected in BALF cells and lung tissue (Supplemental Figure 2D). BALF contained high numbers of macrophages after bleomycin, while neutrophils and lymphocytes were barely detected (Supplemental Figure 2E). Fra-2 protein was detected in alveolar lavage fluid (BALF) was evaluated over time (Supplemental Figure 2C). Fra-2 mRNA expression peaked in BALF and lung at 3 and 10 days after bleomycin, respectively, and preceded collagen accumulation (Figure 2B). TGF-β1 and AAM marker gene expression increase was also detected in BALF cells and lung tissue (Supplemental Figure 2D). BALF contained high numbers of macrophages after bleomycin, while neutrophils and lymphocytes were barely detected (Supplemental Figure 2E). Fra-2 protein was
fibroblast and endothelial cells), while it was expressed in alveolar and conventional macrophages, as well as in neutrophils and eosinophils (Figure 2D). Ten days after bleomycin, Fra-2 GFP expression increased in epithelial cells, CD73+ cells, alveolar macrophages, eosinophils, and a subset of conventional macrophages, but not in neutrophils (Figure 2D). These results indicate that Fra-2–expressing macrophages might contribute to bleomycin-induced lung fibrosis.

detected in mesenchymal cells and macrophages by immunofluorescence (IF) in lung sections, a pattern reminiscent of that in Fra-2ΔAd lungs (Figure 1A), but not in AEC2 cells 14 days after bleomycin (Figure 2C). Fra-2+/– heterozygous mice (31) expressing a GFP reporter controlled by the endogenous Fra-2 regulatory elements were monitored by flow cytometry (Supplemental Figure 3, A and B). Under homeostatic conditions, the Fra-2 GFP reporter was barely detectable in lung epithelial and CD73+ cells (including fibroblast and endothelial cells), while it was expressed in alveolar and conventional macrophages, as well as in neutrophils and in eosinophils (Figure 2D). Ten days after bleomycin, Fra-2 GFP expression increased in epithelial cells, CD73+ cells, alveolar macrophages, eosinophils, and a subset of conventional macrophages, but not in neutrophils (Figure 2D). These results indicate that Fra-2–expressing macrophages might contribute to bleomycin-induced lung fibrosis.
Fra-2 is essential for lung fibrosis development. As germline inactivation of Fra-2 is lethal (31), Fra-2 was locally inactivated in the lung of mice homozygous for a Fra-2-floxed allele (Fra-2<sup>Δ</sup>fl/fl) by intratracheal delivery of adenovirus expressing Cre recombinase (Fra-2<sup>Δ</sup>Ad). This method is widely used to target lung epithelial cells (32), and the resulting Fra-2<sup>Δ</sup>Ad mice were healthy with no lung phenotype for the duration of the experiment (Figure 3A). Flow cytometry analyses of mice treated with adenovirus expressing GFP and bleomycin revealed efficient targeting of epithelial cells, but also mesenchymal cells and all myeloid cells (Supplemental Figure 3C). Fra-2 inactivation resulted in less severe bleomycin-induced fibrosis, with decreased sirius red positive (Figure 3B) and lower hydroxyproline content (Figure 3C) in the lungs of Fra-2<sup>Δ</sup>Ad mice compared with Fra-2<sup>Δ </sup>n littermates receiving empty adenovirus (Figure 3D). Finally, longitudinal plethysmography revealed a somehow milder decline in lung function in Fra-2<sup>Δ</sup>Ad mice 7 and 14 days after bleomycin, with a lower LR/DC ratio compared with that of empty virus littermates (Figure 3D).

Next, Fra-2 was genetically inactivated in AEC2 lung epithelial cells by combining Fra-2 floxed alleles with the tamoxifen-inducible SPC-Cre<sup>ER</sup>T2 knockin allele (33). The resulting Fra-2<sup>Δ</sup>Ad mice were healthy on a tamoxifen diet with no obvious lung alterations. The GFP reporter included in the Fra-2<sup>Δ</sup>Ad mice and expressed instead of Fra-2 upon Cre-mediated gene deletion (Figure 3E) was only detected in a small number of epithelial cells (CD45 EpCAM<sup>+</sup>) in the lungs of Fra-2<sup>Δ</sup>Ad<sup>Cre</sup> mice (Supplemental Figure 3D). This is consistent with the limited expression of Fra-2 in SPC-positive cells after bleomycin (Figure 2, C and D) and confirms that SPC-Cre<sup>ER</sup>T2 does not target Fra-2-expressing hematopoietic cells (CD45<sup>+</sup>). Importantly, Fra-2<sup>Δ</sup>Ad<sup>Cre</sup> mice and Fra-2-proficient littermates developed similar lung fibrosis upon bleomycin instillation with comparable sirius red positivity (Figure 3F), hydroxyproline accumulation (Figure 3G), and LR/DC ratio (Figure 3H). These data unequivocally demonstrate that Fra-2 expression in AEC2 cells is not required for lung fibrosis development and that the milder fibrosis observed in Fra-2<sup>Δ</sup>Ad mice is likely due to Fra-2 inactivation in nonepithelial cells.

Myeloid-specific Fra-2 inactivation reduces, while Fra-2<sup>Δ</sup>Tg BM potentials, lung fibrosis. The constitutively expressed Lys2-Cre knockin allele (34), also called LysM, was used to inactivate Fra-2 in the myeloid lineage (Figure 4A). Fra-2<sup>Δ</sup>Tg mice were healthy, and flow cytometry analyses using the GFP reporter revealed efficient and exclusive recombination of the floxed Fra-2 allele in lung myeloid cells, both in homeostasis and upon bleomycin administration. Increased Fra-2-reporter expression after bleomycin was observed in a large fraction of macrophages and a small fraction of eosinophils, while expression in neutrophils, monocytes, and alveolar macrophages was comparable to that in untreated Fra-2<sup>Δ</sup>Tg mice (Supplemental Figure 4A). Efficient Fra-2 recombination was further confirmed by quantitative reverse-transcription PCR (qRT-PCR) analyses of sorted macrophages, with 85.6% reduction of Fra-2 mRNA in bleomycin-treated Fra-2<sup>Δ</sup>Tg mice (Supplemental Figure 4B), and by immunoblot of lung extracts (Supplemental Figure 4C).

No significant differences in the total number of pulmonary myeloid cells were observed between Fra-2<sup>Δ</sup>Tg and Fra-2<sup>Δ</sup>fl/fl mice 10 days after bleomycin treatment (Figure 4B), indicating that Fra-2 is not essential for the increase in myeloid cells during fibrosis. Lung vessel leakage during the acute inflammatory response to bleomycin was also not different between genotypes (Supplemental Figure 4D). However, bleomycin-treated Fra-2<sup>Δ</sup>Tg mice developed significantly less severe lung fibrosis, with decreased sirius red positivity (Figure 4C), lower collagen packing density (Supplemental Figure 4E), and reduced lung hydroxyproline content in the lung (Figure 4D). As a result, pulmonary function was significantly improved in Fra-2<sup>Δ</sup>Tg mice (Figure 4E). Saline-treated Fra-2<sup>Δ</sup>Tg mice were comparable to saline-treated Fra-2<sup>Δ</sup>Ad mice in all measured fibrosis-related parameters (Figure 4, C–E), and myeloid-specific deletion of a single Fra-2 allele (Fra-2<sup>Δ</sup>/<sup>Δ</sup>; LysM-Cre<sup>+</sup> mice: Fra-2<sup>Δ</sup>Tg<sup>Δ</sup>) was not sufficient to affect collagen accumulation (Figure 4D) or lung function (Supplemental Figure 4F), additionally ruling out that the changes observed in Fra-2<sup>Δ</sup>Tg mice are due to the Lys2-Cre allele. Detailed analyses further revealed decreased induction of ECM genes, such as Coll1 and Fln1 (encoding for fibronectin), and the ECM proteins procollagen type I and fibronectin in Fra-2<sup>Δ</sup>Tg lungs (Supplemental Figure 4, G and H). Interestingly, while total lung mRNA expression of AAM marker genes was decreased 21 days after bleomycin in Fra-2<sup>Δ</sup>Tg mice compared with Fra-2<sup>Δ</sup>fl/fl mice (Supplemental Figure 4I), no difference was observed between these 2 groups in lung macrophages sorted at day 14, except for Nos2 (Figure 4F). Arg1 was significantly upregulated after bleomycin compared with saline, but the increase was not affected by Fra-2 deletion (Figure 4F). These data indicate that, at least in the early phases of fibrosis, Fra-2 expression in myeloid cells is not crucial for the relative number or distribution of macrophage subpopulations or for the polarization of AAM, while it is essential to their fibrogenic activity in vivo.
BM transplantation experiments were next performed to assess whether increased Fra-2 expression in immune cells, particularly in the myeloid lineage, would potentiate fibrosis. WT or Fra-2ΔTg BM was transplanted into lethally irradiated WT mice, which were subsequently subjected to bleomycin (Figure 4G). In this setting, no fibrosis was observed in the saline groups, and regardless of the BM genotype, a milder fibrosis developed 14 days after bleomycin, compared with our previous experiments using nontransplanted mice, in which fibrosis was severe. Importantly, mice reconstituted with Fra-2ΔTg BM accumulated more collagen (Figure 4, H and I) and had worsened lung function (Figure 4J) after bleomycin treatment compared with mice transplanted with WT BM. This demonstrates that ectopic Fra-2 expression in immune cells promotes bleomycin-induced fibrosis.

Overall, these data strongly support an important functional contribution of Fra-2–expressing macrophages to lung fibrosis and suggest a crosstalk between activated macrophages recruited to the lung upon injury and ECM-producing cell types, such as pulmonary fibroblasts.

Macrophages release profibrotic factors in a Fra-2/AP-1–dependent manner. Monocyte-derived macrophages recruited to the lung are major contributors to murine lung fibrosis (35, 36). BM monocytes were therefore isolated from Fra-2Δmic and Fra-2ΔTg mice, differentiated into macrophages (BM-derived macrophages [BMDMs]), and assessed for their ability to induce a fibrogenic response in WT primary lung fibroblasts. BMDMs were differentiated and expanded using macrophage CSF-1 (MCSF-1) and either left untreated or exposed to the AAM-inducing cytokine IL-4 or to the AP-1 activity inhibitor T-5224 (37). Medium was next changed to serum- and factor-free medium, and the cells and their conditioned media (CM) were harvested 48 hours later (Figure 5A). IL-4 pretreatment increased Fra-2 mRNA expression in Fra-2ΔTg, but not in Fra-2Δmic, BMDMs (Figure 5B). Consistent with our in vivo observations, no difference in the expression of M(IL-4) marker genes was observed between the 2 genotypes (Supplemental Figure 5A), and the mRNA induction of Tgfb1, Timp1, and Mmp12 in BMDMs was also comparable between genotypes (Supplemental Figure 5B). These data indicate that macrophage polarization in vitro in response to IL-4 is not substantially affected by Fra-2 inactivation. In an independent experiment, the Fra-2Δmic BMDM expression of CM markers in response to LPS was also largely comparable to that in WT, with the notable exception of higher Ili2a induction (Supplemental Figure 5C).

Incubation of primary lung fibroblasts with CM from IL-4–pretreated BMDM increased cell viability independently of the BMDM genotype (Supplemental Figure 5D). However, increased mRNA expression of the myofibroblast markers Acta2 and Postn, encoding α-SMA and periostin, respectively, was exclusively observed when lung fibroblasts were exposed to CM from IL-4–pretreated Fra-2-proficient BMDMs (Figure 5C). The reduced fibrogenic potential of Fra-2Δmic BMDM CM compared with that in WT was also apparent by α-SMA immunoblot (Figure 5D). The profibrogenic activity of macrophages expressing Fra-2 was next assessed using nonpolarized Fra-2ΔTg BMDMs treated with the AP-1 inhibitor T-5224 (38). Transgene expression was confirmed by qRT-PCR and GFP positivity (Figure 5E and data not shown). Interestingly, mRNA expression of the M(IL-4) macrophage marker Mrcl was decreased in Fra-2ΔTg BMDMs and only affected by T-5224 pretreatment in control BMDMs. Chi3l3 (Ym1) tended to increase in Fra-2ΔTg BMDMs, while the CAM marker hi3l3 was undetectable (Supplemental Figure 5E). Expression of Tgfb1 and Timp1 was not significantly altered, whereas increased Mmp12 mRNA in Fra-2ΔTg BMDMs was attenuated by T-5224 (Supplemental Figure 5F). Importantly, mirroring the Fra-2 loss-of-function setting, exposure to Fra-2ΔTg BMDM CM induced fibrotic gene expression in lung fibroblasts, such as Acta2, which was prevented by AP-1 inhibitor pretreatment (Figure 5F). Collectively, these data indicate that in macrophages, Fra-2 controls the production of profibrogenic factors, but does not substantially alter their polarization.

ColVI chains are secreted by macrophages and are direct Fra-2 transcriptional targets. Macrophages are a major cellular component of the BALF in fibrotic mice (Supplemental Figure 2E), and exosomes often carry disease-specific proteins that could serve as biomarkers and therapeutic targets (39). We isolated exosomes from 2 experimental lung fibrosis paradigms, the spontaneous Fra-2ΔTg and the bleomycin-induced WT mouse models, to find an unbiased representation of molecules secreted by cells in the local microenvironment of fibrotic lungs, including macrophages and possibly other cell types. Exosome-like vesicles were purified from the BALF of fibrotic Fra-2ΔTg (12 weeks) and bleomycin-treated WT mice (12 days; Supplemental Figure 6A). NanoSight analyses revealed a reduced number of vesicles in both fibrosis models compared with nonfibrotic controls, while vesicles were larger in bleomycin-treated mice (Supplemental Figure 6B). Exosomal proteome was analyzed by label-free liquid chromatography–tandem mass spectrometry (LC-MS/MS), and around 400 proteins were identified in the BALF of WT mice with or without bleomycin, while more than 600 proteins were found in fibrotic Fra-2ΔTg mice (Supplemental Figure 6C). Enrichment in extracellular- and vesicle-related protein profiles was confirmed by Gene Ontology analysis (Supplemental Figure 6D) with exosome markers, such as CD63, CD81, Alix, or Hsp90, present in all groups (data not shown). Importantly, the list of protein peptides identified in BALF exosomes from fibrotic, Fra-2ΔTg, and bleomycin-treated WT mice, but not in healthy controls, was enriched in macrophage signatures (Supplemental Figure 6E), suggesting an increase of vesicles of myeloid origin during lung fibrosis. We next compared this list of exosome-derived potential fibrosis biomarkers to the genes found significantly changed in Fra-2Δmic prefibrotic lungs by RNA-Seq. Strikingly, peptides from all 3 ColVI chains, α1, α2, and α3, were present in BALF exosomes from fibrotic mice (Figure 6A and Supplemental Figure 6F), and their respective mRNAs, Col6a1, Col6a2, and Col6a3, were upregulated in prefibrotic Fra-2Δmic lungs (Supplemental Figure 6G). In the bleomycin model, Col6a1, Col6a2, and to a lesser extent, Col6a3 mRNA were increased in the lungs of Fra-2Δmic mice at 21 days, but not in Fra-2Δmic mice (Figure 6B). ColVI is a nonfibrillar collagen formed by trimers of α1, α2, and α3 chains that can promote fibroblast migration (40) and be secreted by macrophages (41). ColVI was coexpressed with Fra-2 in Ym1-positive, alternatively activated macrophages in fibrotic lungs of bleomycin-treated mice and also in fibrotic lungs sections of an independent experimental model of fibrosis (42), γ-herpesvirus-infected (MHVΔ8) IFN-γ receptor KO (IFNγR–) mice (Supplemental Figure 6H). Additionally,
Figure 5. CM from Fra-2-expressing BM-derived macrophages induces lung fibroblast activation. (A) Experimental design to assess the effect of BMDM conditioned medium on WT primary lung fibroblasts. Experiment was repeated 5 and 2 times for the Fra-2 loss and gain of function, respectively. Each individual value represents a biological replicate, since each BMDM culture originates from 1 individual mouse. IL-4 was added at 20 ng/mL, T-5224 at 3 μM, and TGF-β1 at 0.5 ng/mL. (B) Fra-2 expression in BMDMs when CM was collected (qRT-PCR). Note that specific primers located in the floxed/deleted exons (Ex3-Ex4) are used. *P < 0.05; **P < 0.01, 1-way ANOVA; Bonferroni’s post test. (C) qRT-PCR analysis of fibroblast marker genes in primary WT lung fibroblasts cultured with CM and TGF-β1 (positive control). *P < 0.05; ***P < 0.001, 1-way ANOVA; Bonferroni’s post test. Group analysis for each gene. TGF-β1, n = 3; other groups, n ≥ 7. (D) Immunoblot analysis of procollagen I and α-SMA in primary lung fibroblast lysates. Relative densitometry quantification for each protein is shown as a ratio to vinculin density (loading control). Individual values and mean ± SEM from 1 experiment are plotted. *P < 0.05, unpaired t test; 1-tailed. Pro-col I, procollagen I. (E) Fra-2 expression in WT and Fra-2Tg BMDMs at the time the CM was collected (qRT-PCR). ***P < 0.001, 1-way ANOVA; Bonferroni’s post test. (F) qRT-PCR analysis of fibroblast marker genes in primary WT lung fibroblasts cultured with WT and Fra-2Tg BMDM-CM. *P < 0.05; **P < 0.01, paired 2-tailed t test. In all panels, bars represent mean ± SD/SEM. Relative mRNA and protein expression in untreated Fra-2fl/fl BMDMs and derived CM is set to 1.
ColVI protein expression in the lungs was significantly induced by bleomycin in WT mice compared with Fra-2–/– mice (Figure 6C) as well as in Fra-2–/– BM chimeras compared with WT BM chimeras (Supplemental Figure 6I). Comparing Col6a gene expression in macrophages and mesenchymal and epithelial cells FACS sorted 14 days after bleomycin revealed that, although PDGFRα-positive mesenchymal cells have the highest relative ColVI expression when normalized to cell number, F4/80-positive macrophages are the only cell type in which the 3 ColVI genes are robustly induced by bleomycin (Supplemental Figure 7A). Furthermore, the increase in Col6a gene expression in lung macrophages FACS sorted 10 days after bleomycin (Figure 6D) or in IL-4–pretreated BMDMs (Supplemental Figure 7B) was largely Fra-2 dependent, as it was not observed in Fra-2–/– cells. Interestingly, Fra-2 did not appear to be essential for the in vitro induction of Col6a genes by TGF-β1 in primary lung (Supplemental Figure 7C) or embryonic (Supplemental Figure 7D) fibroblasts.

Collectively, these data indicate that, under fibrotic conditions, ColVI expression is increased in macrophages in 3 independent lung fibrosis paradigms in a Fra-2–dependent manner.

Inspection of the murine Col6a genes revealed several Fra-2/AP-1 dimer binding (TRE) elements in regulatory regions (Supplemental Figure 7E). ChiP-qPCR assays using in vitro–cultured BMDMs and specific Fra-2 antibodies demonstrated Fra-2 binding to TRE-containing promoter regions of Col6a1, Col6a2, and Col6a3 in Fra-2–/– and in Fra-2–/– BMDMs pretreated with IL-4, but not in Fra-2–deficient BMDMs (Figure 6E), indicating that Col6a genes are direct Fra-2/AP-1 target genes in myeloid cells, implicated in the profibrogenic action of macrophages.

ColVI deficiency decreases fibrosis in vitro and in vivo. WT primary lung fibroblasts express higher Acta2 when plated on ColVI (Supplemental Figure 8A). Primary lung fibroblasts exposed to CM from IL-4–pretreated Col6a1-KO (43) BMDMs (ColVI–/–) failed to induce Acta2 compared with WT BMDMs (Figure 6F), while M (IL-4–) marker genes were similarly induced (Supplemental Figure 8B). Interestingly, CM from IL-4–treated ColVI–/– BMDMs induced Col3a1 mRNA in fibroblasts (Figure 6F), while the alterations in Col3a2 mRNA and procollagen type I proteins were not significant (Figure 6F and Supplemental Figure 8C). Nevertheless, these in vitro data suggest that, similar to what occurs in Fra-2–deficient cells, IL-4-polarization of ColVI-deficient macrophages is unaltered, while their profibrotic paracrine potential is impaired.

To evaluate the profibrotic role of ColVI in vivo, ColVI–/– mice were subjected to the bleomycin lung fibrosis paradigm. qRT-PCR analyses confirmed increased Col6a1 gene expression in bleomycin-treated WT controls, which was undetectable in ColVI–/– mutants (Supplemental Figure 8D). Importantly, while macrophage numbers were not overtly affected (data not shown), the ECM components type I collagen and fibronectin accumulated significantly less in ColVI-deficient lungs, and Fra-2 expression was reduced (Figure 6G and Supplemental Figure 8, E and F). Furthermore, lung function was significantly improved in ColVI-deficient mice 14 days after bleomycin (Figure 6H). We next treated lethally irradiated WT mice, reconstituted with either WT or ColVI–/– BM, with bleomycin (Figure 6I and Supplemental Figure 8G). Mice transplanted with ColVI–/– BM were protected from bleomycin-induced lung fibrosis compared with mice that received WT BM, with decreased type I collagen accumulation (Figure 6I), decreased sirius red positivity (Supplemental Figure 8H), and improved respiratory function 21 days after bleomycin treatment (Figure 6K). Taken together, these experiments clearly demonstrate a critical functional role of ColVI expression in immune cells, such as macrophages, during lung fibrosis.

Pharmacological AP-1 inhibition ameliorates fibrosis in the bleomycin model and in Fra-2–/– mice. We next tested the therapeutic potential of the AP-1 inhibitor T-5224 (37). Saline- or bleomycin–treated WT mice were randomized at day 14, when the acute inflammation phase had subsided and fibrosis had developed, for daily T-5224 or vehicle (polivinlypyrrrolidone [PVP]) oral gavage over 1 week (Supplemental Figure 9A). Under these conditions and consistent with the previously reported benefits of T-5224 when supplied from day 10 (44), bleomycin-induced lung hydroxyproline was significantly lower in T-5224–treated mice than the vehicle-treated cohort (Supplemental Figure 9B). Pulmonary ColVI expression was also reduced (Supplemental Figure 9C), and most importantly, longitudinal plethysmography revealed a significant improvement in lung function with T-5224, with an LR/DC ratio almost reaching the values measured in mice that did not receive bleomycin (Supplemental Figure 9D).

We next treated 12-week-old already fibrotic Fra-2–/– and WT littermates with T-5224 or PVP over 4 weeks (Figure 7A). As previously reported (38), extended T-5224 treatment was well tolerated and did not alter body weight (Supplemental Figure 9E). Importantly, T-5224 resulted in significantly less collagen accumulation in the lungs of Fra-2–/– mice as measured at end point by sirius red positivity (Figure 7B and Supplemental Figure 9F) and hydroxyproline content (Figure 7C). Gene and protein analyses further confirmed ECM components, such as fibrillar collagens I and III.
and fibronectin, were less expressed in the lungs of Fra-2Tg mice treated with T-5224 (Figure 7D and Supplemental Figure 9G). In T-5224-treated lungs, Fra-2 mRNA, protein, and the number of Fra-2-positive cells were decreased, while IL-4 appeared unaffected (Figure 7, D and E, and Supplemental Figure 9, H and I). With the notable exception of decreased Arg1 and Nos2, end-point mRNA expression of AAM and CAM marker genes was also minimally affected by T-5224 (Supplemental Figure 9I). Increased ColVI protein and Col6a3 mRNA was still apparent in the lungs of Fra-2Tg mice at end-stage disease, but was attenuated by T-5224.

Figure 7. AP-1 inhibition reverts lung fibrosis in Fra-2Tg mice. (A) Schematic for AP-1 inhibitor T-5224 therapeutic protocol in Fra-2Tg mice. All data originate from 3 independent experiments designed as randomized blocks. Asterisks indicate when the plethysmography was performed within the experiment timeline. (B) Quantification of sirius red-positive areas in lungs at the end of the experiment. **P < 0.01, 1-way ANOVA; Bonferroni’s post test. (C) Hydroxyproline content in lungs (left lobe). ***P < 0.001, 1-way ANOVA; Bonferroni’s post test. (D) Immunoblot analysis of Fra-2, procollagen I, type I collagen, and fibronectin in lung lysates at the end of the experiment. Band density quantification is shown in the graph, with individual values relative to vinculin (loading control). **P < 0.01, unpaired 2-tailed t test. (E) Quantification of Fra-2-positive nuclei in lung IF relative to total cells. *P < 0.05, unpaired 2-tailed t test. (F) qRT-PCR analysis of ColVI genes in the lungs of Fra-2Tg and WT controls treated with T-5224 or PVP at the end of the experiment. Relative expression in WT+PVP is set to 1. *P < 0.05; **P < 0.01, 1-way ANOVA; Bonferroni’s post test. (G) Quantification of lung ColVI-positive area in IHC staining. *P < 0.05, 1-way ANOVA; Bonferroni’s post test. (H) Longitudinal analyses of respiratory function of Fra-2Tg and WT controls with T-5224 or vehicle. Note that the T-5224 or vehicle treatment started around 12 weeks of age, when animal respiratory function was already compromised (arrow). *P < 0.05; **P < 0.01; ***P < 0.001, 2-way ANOVA; Bonferroni’s post test.
Figure 8. Fra-2 and ColVI expression in human lung fibrosis. (A) Gene expression values of COL1A2 in lungs from human patients with normal histology (normal; n = 173) and diagnosed ILD (n = 255) and COPD (n = 219). Expression values were obtained from the public gene expression database of the LGRC (GSE47460). **P < 0.01; ***P < 0.001, 1-way ANOVA; Bonferroni’s post test. (B) Gene expression values of FOSL2 (Fra-2), COL6A1 (ColVI chain α1), and COL6A3 (ColVI chain α3) genes in lungs from same cohort. Note that expression values for COL6A2 (ColVI chain α2) were absent in the data set. *P < 0.05; **P < 0.01; ***P < 0.001, 1-way ANOVA; Bonferroni’s post test. (C) Expression values for FOSL2 are plotted against COL6A3 for linear regression and Pearson’s correlation analysis of normal and ILD samples (r² and P values are indicated). (D) Gene expression values of ColVI genes in lungs from human patients with normal histology (normal) and diagnosed IPF. Expression values were obtained from a public curated data set (GDS1252). *P < 0.05; **P < 0.01, 2-tailed paired t test. (E) Triple IHC for Fra-2 (brown-nuclear), CD68 (blue-cytoplasmic), and ColVI (purple-extracellular) of human lungs from healthy and fibrosis patients. Nuclei are counterstained with hematoxylin. Arrows point to interstitial macrophages expressing Fra-2 and colocalizing with ColVI (triple positive); arrowheads point to Fra-2–positive alveolar macrophages. Scale bars: 100 μm (low magnification); 20 μm (high magnification). (F) Working model for the role of Fra-2/ColVI in macrophages during lung fibrosis.
treatment (Figure 7, F and G). Most strikingly, longitudinal plethysmography revealed a clear functional benefit of T-5224, as it halted the progressive decline in Fra-2\textsuperscript{Tg} lungs. LR/DC remained stable in T-5224-treated mutants, while it further worsened in vehicle-treated Fra-2\textsuperscript{Tg} mice (Figure 7H). These data demonstrate that lung fibrosis is substantially ameliorated by therapeutic AP-1 inhibition in 2 experimental models of fibrosis and that AP-1 pharmacological inhibitors such as T-5224 should therefore be considered for lung fibrosis therapy.

ColVI and Fra-2 are coexpressed in human fibrotic lungs and macrophages. Finally, we assessed Fra-2 and collagen gene expression in human disease by computational analysis of the Lung Genomics Research Consortium (LGRC) database, with gene expression data from diseased lung tissue from 255 ILD and 219 chronic obstructive pulmonary disease (COPD) patients and normal lung tissue from 173 thoracic surgery patients (GSE47460). The fibrosis marker COLA2 (type I collagen) was increased in both diseased cohorts (Figure 8A). Importantly, while COL6A1 was higher in patients with both ILD and COPD compared with healthy individuals, FOSL2 and COL6A3 were specifically increased in ILD samples, but not in COPD samples (Figure 8B). Increased FRA-2 and COLVI were observed in lung protein extracts from an independent patient cohort (data not shown). Furthermore, the expression of FOSL2 and COL6A3 positively correlated across ILD and healthy samples (Figure 8C). A similar analysis using an independent data set for IPF (GDS1252) also showed increased mRNA expression of COL6A1 and COL6A3 and indicated that COL6A2 is also increased in IPF lung samples compared with healthy lungs (Figure 8D and ref. 45). Importantly, both alveolar and interstitial macrophages highly express Fra-2 in lung sections from fibrosis patients when compared with healthy tissues. Furthermore, Fra-2, ColVI, and CD68 (human macrophage marker) triple immunohistochemistry indicated that interstitial macrophages expressing Fra-2 also express ColVI (Figure 8E). These results indicate that Fra-2 expression in AAMs contributes to mouse and human lung fibrosis, possibly by controlling the expression of secreted factors, such as ColVI.

Discussion
The role of the immune response in lung fibrosis and its potential as a therapeutic target are not clearly established. Here, we provide evidence for a functional contribution of Fra-2–expressing macrophages to the paracrine activation of fibroblasts and to lung fibrosis (Figure 8F). We identify ColVI as a Fra-2 transcriptional target in macrophages and unravel a profibrogenic role for ColVI in vitro and in vivo. Importantly, inhibiting Fra-2/AP-1 or ColVI is therapeutically relevant in mouse models of lung fibrosis.

The fibrotic phenotype in the Fra-2\textsuperscript{Tg} model of fibrosis is reminiscent of a type 2 cytokine–driven disease with enhanced IL-4 expression, IL-4 pathway signature, eosinophil/neutrophil infiltration, and M(IL-4) macrophage enrichment (25, 28, 46). The contribution of type 2 cytokines, IL-4 and IL-13, to macrophage activation and fibrosis development in different organs is well accepted (4, 47, 48). Lung-specific expression of these cytokines increases after bleomycin treatment, although their importance in this particular lung fibrosis model is controversial (49–51). While type 2 cytokines seem dispensable or even detrimental in the early phases after bleomycin treatment, these likely promote subsequent fibrotic events (52, 53). IL-4 and IL-13 induce Fra-2 expression in macrophages (ref. 54 and our in vitro data) and promote profibrotic macrophage activation and myofibroblast differentiation (14, 55, 56). We demonstrate that Fra-2 expression in macrophages is not essential for the early inflammatory phase of bleomycin-induced fibrosis nor for macrophage recruitment or phenotypic switch, but modulates the expression of molecules produced by M(IL-4) macrophages to promote the differentiation of fibroblasts to myofibroblasts and lung fibrosis. This is particularly relevant, as clinical trials for IPF and other type 2 immunity diseases using blocking antibodies against type 2 cytokines had limited success, likely due to exacerbation of type 1 (Th1) inflammation or impaired tissue regeneration (57, 58). New strategies decreasing the profibrotic arm of type 2 (Th2) inflammation and/or targeting AAMs secretory/paracrine activity without affecting tissue repair and Th1 inflammation are therefore urgently needed.

Macrophage-secreted factors, such as platelet-derived growth factor (PDGF), TGF-β1, MMPs, and tissue-inhibitor metalloproteinases (TIMPs), can induce and sustain fibroblast-to-myofibroblast activation (59–63). This and the recently proposed direct transition from macrophages to myofibroblasts (64) defines the current understanding of macrophage-fibroblast crosstalk in wound healing and fibrosis. PDGF and TGF-β signaling modulate vascular remodeling in Fra-2\textsuperscript{Tg} mice, but appear largely dispensable for lung fibrogenesis (28, 65). No MMPs/TIMPs were found consistently deregulated in the lung, macrophage, and/or BMDM cultures across the different experimental models used in the current study. Instead, we unraveled an important contribution of ColVI, a direct transcriptional target of Fra-2/AP-1 in macrophages, in modulating fibroblast activation in vitro and fibrogenesis in vivo. We provide experimental evidence for this Fra-2/ColVI connection in 3 independent experimental models of lung fibrosis — chemical, virus, and transgene induced (25, 42, 66) — as well as in patient samples. In the bleomycin model, we show for what we believe is the first time that ectopic Fra-2 expression in BM promotes lung fibrosis, while myeloid-specific Fra-2 inactivation as well as complete or BM-derived ColVI deficiency is protective. While the contribution of other BM-derived cell types cannot be excluded in the transplantation experiments, our collective data in vitro and in vivo suggest that monocyte/macrophages expressing Fra-2 are a relevant functional source of profibrotic ColVI. A more definitive assessment of the contribution of ColVI-expressing macrophages in vivo would require the generation of a new mouse model with conditional ColVI alleles and/or efficient and long-term engraftment of adoptively transferred ColVI-deficient monocytes. Both experimental strategies are challenging and time consuming. As Fra-2 and ColVI are broadly expressed in other fibrosis-relevant lung cell types, such as in mesenchymal cells, future investigations using the appropriate cell-specific genetic tools are certainly warranted for exploring and fully determining the functional role of these 2 genes in the lung and also in tissue fibrosis.

Monocyte-derived macrophages are key drivers of lung fibrosis, replenishing alveolar macrophages immediately lost upon injury (35, 36, 67). While macrophage depletion during wound healing resulted in antagonistic phase-dependent outcomes (68), it
prevented fibrosis in several models (69,70), including bleomycin-induced lung fibrosis (11, 63, 71, 72). Nintedanib, the first-line treatment for IPF, is a potent inhibitor of several growth factor receptors, including the macrophage-survival cytokine M-CSF-R. Nintedanib reduces circulating M-CSF and skin AAMs in Fra-2ΔΔ mice and ameliorates skin and lung fibrosis (46). ColVI expression by macrophages promotes lung fibroblast activation, but similarly to Fra-2, is not essential for the macrophage phenotype switch. Consistent with the implication of AP-1 proteins Fra-2 and c-Jun and the AP-1–activating JNK kinases in lung fibrosis (73, 74), pharmacological AP-1 inhibition decreased ColVI expression and substantially ameliorated bleomycin- and Fra-2ΔΔ-induced fibrosis. Therefore, unlike conventional strategies aiming at depleting macrophages or blocking IL-4/IL13/Th2 response, the more restricted outcome of targeting Fra-2/ColVI using compounds such as T-5224 would provide a therapeutic opportunity to block the profibrogenic arm of chronic Th2-associated diseases without affecting proregenerative effectors.

Increased ColVI in IPF patient lung sections was reported (75). We now show that Fra-2 and ColVI are coexpressed in human IPF lung macrophages and specifically increased and correlated in ILD, but not inflammatory COPD, indicating that coexpression of Fra-2 and ColVI could be a better biomarker for lung fibrosis than type I collagen, which is increased in both diseases. Whether, similarly to what occurs with Fra2ΔΔ and bleomycin-treated mice, ColVI peptides are detectable in BALF exosome-like vesicles from IPF patients undergoing diagnostic bronchoscopy awaits experimental evaluation. In conclusion, Fra-2–expressing macrophages and ColVI are two therapeutically relevant determinants of paracrine fibroblast activation and tissue fibrogenesis. Further work will likely identify additional Fra-2/ AP-1–regulated molecules that could be targeted therapeutically and stimulate the development of specific drugs for these largely untreated human diseases.

Methods

Mouse procedures. H2kb-fosl2-LTR, Lyz2-Cre, sfpc-CreERT2, col6a1ΔΔ, and fosl2ΔΔ alleles are described elsewhere (25, 31, 43, 76). All mouse lines were maintained on a C57BL/6 background and housed in a specific pathogen-free facility accredited by the American Association for Laboratory Animal Care (AALAC), with food and water ad libitum. Male mice were anesthetized by i.p. injection of medetomidine (Domitor) and ketamine (Imalgene), intubated with a 24-gauge catheter (BD), and instilled with a single dose of 1.5 U/kg of bleomycin (Millipore Sigma). Anesthesia was reverted with atipamezole and dexterox. Bleomycin-treated and Fra-2Tg mice were monitored by body catheter (BD), and instilled with a single dose of 1.5 U/kg of bleomycin (Bhubaneswar) into the trachea of mice infused to complete single pm injection. Male mice were anesthetized by i.p. injection of medetomidine (Domitor) and ketamine (Imalgene, Merial Laboratories), intubated with a 24-gauge catheter (BD), and introduced in the chamber of a plethysmograph (EMKA). A MiniVent (Harvard Apparatus) was connected to the plethysmograph and the tracheal cannula for animal ventilation at 10 ml/kg of tidal volume and 150 breaths per minute. Data were measured by 2 pressure transducers that detect pressure variations in the chamber (flow) and in the tracheal cannula (pressure). This allows for measurements of LR (mmHg/mL x s⁻¹) and DC (mL/mmHg) in addition to other lung function parameters. Lung function measurement was repeated at least 3 times and the data averaged for each mouse. Fibrotic lungs show increased LR and decreased DC (reduced tissue elasticity).

Cell culture. Primary mouse lung fibroblasts were isolated from adult mice. Lungs were perfused with saline to eliminate blood cells and lung tissue was minced and incubated for 45 minutes in serum-free media with 0.14 Wunsch units/mL Liberaze Blendzyme 3 (Roche). After centrifugation, the pellet was resuspended in 20% FBS and 1% penicillin-streptomycin-supplemented DMEM/F12 culture media (Lonza). Cells attaching from the tissue pieces were trypsinized and cultured in monolayer. When confluent, CD45-negative cells were sorted to purify the cell culture from possible hematopoietic cell contamination. All lung fibroblasts were used between passages 3 and 5.

Primary BMDMs were isolated from adult mice by differentiation of BM-derived monocytes with incubation of 3 to 5 days with 50 ng/mL of mouse MCSF-1 (R&D and Prepotech) in bacteria plates. Before confluence, cells were trypsinized, counted, and plated again at a similar number for the experiments. Mouse IL-4 (Prepotech) was added at a concentration of 20 ng/mL, while the AP-1 inhibitor T-5224 was added at 3 μM. LPS was added at 1 μg/mL. For CM experiments, cells were cultured in serum- and phenol red-free media. When collected, supernatants were centrifuged, filtered through a 45 μm filter, and aliquoted before storage. Fibronectin, Coll, and ColVI were used to precoat culture dishes (20 μg/mL). Primary lung fibroblasts were harvested for RNA analysis 24 hours after plating. Fra-2ΔΔ mouse lung RNA-Seq data were deposited in the NCBI’s Gene Expression Omnibus database (GEO GSE103355).

For further information, see Supplemental Methods. See complete unedited blots in the supplemental material.

Statistics. Unless otherwise specified, data are expressed as mean ± SEM and individual values are plotted. Statistical significance was determined using either paired or unpaired t test (1 or 2 tailed) or Mann-Whitney U test according to sample distribution for comparing 2 groups of samples. One-way ANOVA or two-way ANOVA was performed for grouped or multivariate analysis, as appropriate. For all experiments, P < 0.05 was considered statistically significant.

Study approval. All animal studies were approved by the CNIO IACUC, by the ethics and animal welfare committee of the the Instituto de Salud Carlos III (Madrid, Spain) and by the Comunidad de Madrid (Madrid, Spain), in accordance with National and European regulations. In the case of the MHV68–induced lung fibrosis mouse model, the protocol was approved by the Emory University Institutional Animal Care and Use Committee and in accordance with established guidelines and policies at Emory University School of Medicine (pro-
tocol YER-2002245-031416GN). The protocol was also carried out in strict accordance with the recommendations in the *Guide for the Care and Use of Laboratory Animals* (National Academies Press, 2011). The project design to obtain human samples was approved by the ethical committee of the Instituto de Salud Carlos III (Madrid, Spain). In addition, samples and/or data from patients included in this study were provided by the Biobanco i+12 in the Hospital 12 de Octubre integrated in the Spanish Hospital Biobanks Network (RetBioH; www.redbiobancos.es) following standard operation procedures, with appropriate approval of the Ethical and Scientific Committees, Madrid Spain. Paraffin-embedded tissue sections and OCT-embedded fresh tissue from 11 pulmonary fibrosis patients and 3 controls without any lung pathology were obtained. All patients provided informed consent.

**Author contributions**

ACU designed and performed experiments and wrote the paper. LB contributed to mouse colony management, experimental design, and manuscript writing. MS contributed to experimental design and provided the data for the bleomycin experiment in WT mice. BR designed and analyzed flow cytometry experiments and contributed to manuscript writing. MJ contributed to experimental design and performed some of the experiments. CPT analyzed the RNA-Seq data. PXE acquired and analyzed LC-MS/MS data. AIH synthesized the T-5224 inhibitor. DM acquired and analyzed confocal microscopy images. P Braghetta and P Bonaldo provided the COLVI-deficient mice and bones for in vitro and in vivo experiments. PM provided data and samples from the MVH68 model. LPA provided access to the human lung samples. EFW directed the study, approved the data, and edited the paper.

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