Introduction

Chronic lung injury resulting from a variety of different causes is frequently associated with the development of pulmonary fibrosis in humans. Although the etiology of pulmonary fibrosis is generally unknown, several sources of evidence support the hypothesis that a number of environmental and occupational agents play an etiologic role in the pathogenesis of this disease. The agents discussed in this review include beryllium, nylon flock, textile printing aerosols, polyvinyl chloride and didecyl dimethyl ammonium chloride. The authors also describe a variety of animal models, including genetically modified mice, in order to investigate the molecular mechanism of pulmonary fibrosis, focusing on chemokine receptors, regulatory T cells and transforming growth factor-β and bone morphogenetic protein signaling. Overall, we propose the concept of toxicological pulmonary fibrosis as a lung disease induced in response to environmental cues. (DOI: 10.1293/tox.24.9; J Toxicol Pathol 2011; 24: 9–24)

Key words: beryllium, nylon flock, DDAC, TGF-β, chemokine receptor, regulatory T cell
Profibrotic Environmental Cues

and zirconium) can produce pulmonary lesions similar to those of sarcoidosis.2 The agents discussed in this review include beryllium, nylon flock, textile printing aerosols, PVC and didecyldimethylammonium chloride (DDAC) (Table 2). Common ILD-causing drugs include amiodarone, antibiotics, nonsteroidal anti-inflammatory drugs, chemotherapeutic agents (e.g., bleomycin and methotrexate) and nitro drugs, all of which can produce virtually all the histopathologic patterns of interstitial pneumonia, including NSIP, OP, DIP and a pulmonary granulomatosis-like reaction. However, this review does not include drug-induced ILDs, except for a bleomycin animal model, for discussing the mechanism of pulmonary fibrosis.

The pathogenesis of pulmonary fibrosis is complex, involving innate and adaptive immunoreactions against exogenous environmental cues and subsequent molecular and cellular responses, leading to an imbalance of profibrogenic and antifibrogenic effects in healing processes. This review also focuses on specific pathobiological mediators such as chemokines and chemokine receptors, regulatory T cells (Treg) and transforming growth factor-β (TGF-β) and bone morphogenetic protein (BMP) signaling.

Beryllium

Beryllium, which mostly occurs naturally as beryllium aluminum silicate, is the fourth lightest element, having a low density (1.85 g/cm³ at 20 °C), high melting point

### Table 1. Histopathological Pattern of Interstitial lung Diseases (ILD)3–5

| Clinical diagnosis | Pathology | Key features |
|--------------------|-----------|-------------|
| NSIP               | NSIP      | Cellular pattern: Mild to moderate interstitial chronic inflammation with hyperplastic pneumocytes. Fibrosing pattern: Diffuse thickening of alveolar walls by dense or loose connective tissues and interstitial chronic inflammation (basically lacking the UIP pattern and preserving alveolar architecture). |
| RB                 | RB-ILD    | Bronchiolocentric accumulation of alveolar macrophages (laden iron) with mild bronchiolar fibrosis and chronic inflammation. |
| COP                | OP        | Patchy plugs of loose connective tissues within a bronchiole, the adjacent alveolar ducts and alveolar spaces and with mild interstitial chronic inflammation. |
| DIP                | DIP       | Marked alveolar accumulation of macrophages (laden iron) with mild interstitial thickening and chronic inflammation. |
| LIP                | LIP       | Diffuse thickening of alveolar walls by infiltration of T cells, plasma cells and macrophages and MALT hyperplasia. |
| AIP                | DAD       | Diffuse alveolar wall thickening by proliferation of connective tissues, inflammation and deposition of hyaline membranes. |
| IPF                | UIP       | Patch fibrosis with remodeling of the lung structures, fibroblast foci, dense collagenous scar, overlying hyperplastic pneumocytes and cystic changes (honeycomb change lined by columnar respiratory epitheliums). |

**Table 2. Environmental and Occupational Agents and Pulmonary Fibrosis**

| Chemicals | Disease | Key factors/Mechanism | References |
|-----------|---------|------------------------|------------|
| Beryllium | ABD/CBDΨ | Hypersensitivity, oxidative stress | 10, 11, 16, 23, 24 |
| Nylon flock | Flock Worker’s Lung# | Hypersensitivity, iron-mediated | 30–32 |
| Textile paint | Ardystil syndromeξ | Acramine F | 37–41 |
| PVC | Pulmonary fibrosisΨ | Residual additives, eosinophilia | 43–45, 50–52 |
| DDAC | ¶ | Cytotoxicity, inflammation | 63–65, 69 |

PVC, polyvinyl chloride; DDAC, didecyldimethylammonium chloride; ABD, acute beryllium disease; CBD, chronic beryllium disease. Diagnosed as lymphocytic bronchiolitis and peribronchiolitis with lymphoid hyperplasia. Diagnosed as organizing pneumonia. With a granulomatous reaction. Pulmonary fibrosis has not been reported, but asthma might occur based on epidemiological studies.
(1287 °C) and high tensile strength, and these properties have led to its incorporation into many high-technology applications (e.g., electronics, aerospace, machinery and nuclear weapons manufacture)8,9. Exposure to beryllium at workplaces continues to be a public health concern, with approximately one million individuals exposed and potentially at risk of developing acute beryllium disease (ABD) and chronic beryllium disease (CBD), both of which involve hypersensitivity reactions to beryllium10,11. Genetic susceptibility to CBD has been linked to a major histocompatibility complex (MHC) class II isotype, human leukocyte antigen (HLA)-DP alleles, which contain a glutamic acid residue at amino acid position 69 in the β-chain12–14. Among the mouse strains FVB/N, AKR, Balb/c, C3H/HeJ, C57/BL6, DBA/2 and SJL/J, the FVB/N strain has been reported to be the least responsive, while the SJL/J and C57/BL6 strains have been shown to be the highest responders15.

CBD is characterized by the presence of noncapsulating granulomatous inflammation in the lung and subsequent development of progressive fibrosis16. Accumulating evidence clearly suggests that CBD is recognized as an immune-mediated granulomatous reaction. Six to nine months after a single exposure of A/J and C3H/HeJ mice to beryllium for 90 min, lung responses comprised interstitial aggregates of lymphocytes—B cells centrally and T cells peripherally—and granulomatous pneumonia characterized by intra-alveolar foamy macrophages, giant cells and neutrophils, and multifocal interstitial granulomas17. Evidence suggests that recruitment of beryllium-specific CD4+ T cells to the lung significantly mediates the immunopathogenesis of CBD. These CD4+ T cells expressed an effector memory T cell phenotype10,13 and secreted the T helper 1 cytokines interferon-γ (IFN-γ), interleukin-2 (IL-2) and tumor necrosis factor-α (TNF-α) upon beryllium exposure18–20. Programmed death-1, which is a member of the PD-1 family of immune checkpoints, is upregulated in CBD patients10,21. Beryllium-specific CD8+ T cells may play a minor role, if any, in the pathogenesis of this disease, as inferred from the results of analysis of BAL samples from CBD patients10.

Beryllium-induced oxidative stress plays a role in the pathogenesis of granulomatous inflammation in CBD. A decrease in intracellular thiols, glutathione and cysteine was observed in peripheral blood mononuclear cells from beryllium-sensitized and CBD patients, and beryllium-mediated T cell proliferation was inhibited by the thiol antioxidant N-acetylcysteine and the catalytic antioxidant manganese (III) in vitro22. Increased glutathione in lung epithelial lining fluid from CBD patients is correlated with glutathione peroxidase activity23. Heme oxygenase-1 (HO-1) activity is also increased in induced sputum from CBD patients24. Together, the data imply that augmentation of glutathione- and HO-1-mediated antioxidant systems may be involved in the process of CBD.

Although cellular and molecular mechanisms underlying berylliosis have been investigated, the exact profibrogenic factors have not been identified thus far. Mast cells may contribute to the pathogenesis of CBD, serving as an important source of a 17.8-kDa isoform of basic fibroblast growth factor, which is a potent mitogenic and chemotactic factor, regulating fibroblast proliferation and ECM production25. In contrast, beryllium at low concentrations inhibits the growth of normal human fibroblasts, as proved by G0–G1/pre-S phase arrest and senescence associated with elevation of the p53, p21 and p16 levels26,27. At high concentrations, beryllium is somewhat carcinogenic to BALB/c-3T3 cells (mouse embryonic fibroblast cell line)28. TGF-β signaling in CBD has not been fully investigated, although Jonth et al. (2007) have reported that the codons −509 C and 10T, implicated in the production of low levels of TGF-β protein, are shared susceptibility factors associated with more severe granulomatous inflammation in CBD29. Thus, investigations of profibrogenic/antifibrogenic signaling would provide a better understanding of the pathobiology of CBD and aid in exploring therapeutic targets.

**Nylon Flock and Textile Paints**

Flock is cut or pulverized fiber—synthetic or natural—of small diameter that produces a velvet-like coating when applied to an adhesive-coated fabric or other material. Flocked fabrics of nylon (polyamide), rayon (cellulose acetate), Dacron (ethylene glycol-terephthalic acid) and polyester fibers are becoming increasingly popular, especially as upholstery coverings and blankets. Kern et al. (2000) reported a chronic nongranulomatous ILD termed “Flock Worker’s Lung” in nylon flocking industry workers at a Rhode Island plant in the 1990s30. The workers developed BAL eosinophilia, NSIP, OP and/or lymphocytic bronchiolitis and interstitial fibrosis. A small number of North American patients have also been reported to have nylon flock-related DIP. At a clinical pathology workshop hosted by the National Institute for Occupational Safety and Health, consulting pulmonary pathologists diagnosed “lymphocytic bronchiolitis and peribronchiolitis with lymphoid hyperplasia” in workers at 5 nylon flocking facilities in 3 different U.S. states and a Canadian province, on the basis of clinical examination and histopathological findings31. This descriptive terminology was supported by the Centers for Disease Control (CDC) at a clinical-pathological workshop hosted by the CDC32.

Although nylon fibers may act as haptens and trigger an allergic reaction (e.g., occupational asthma)33, in vivo experiments have failed to demonstrate pulmonary hypersensitivity reactions to nylon. Airborne dust (nylon flock) collected at a nylon flocking plant interacted with alveolar macrophages and induced mild-to-moderate, multifocal, suppu-
ative pneumonia around bronchioles after intratracheal instillation in rats (10 mg/kg body weight)\textsuperscript{34}. In rats exposed to aerosols of uncoated, finish-free nylon respirable-sized, fiber-shaped particulates at 6 hours per day and 5 days per week for 4 weeks, there were no significant increases in lung weight, indications of pulmonary inflammation or alveolar macrophage functional deficits, as compared with the control rats\textsuperscript{35}. Thus, since workers exposed to high concentrations of nylon fiber dust may be at an increased risk of ILDs, suitable animal models should be developed to clarify the role of nylon fiber in immune-based pulmonary diseases.

Synthetic fibers do not include metals. Synthetic fibers present an insoluble solid-liquid interface to the surrounding host tissue, and the fiber surface includes functional groups having the ability to mobilize metal from endogenous sources, introducing a metal-catalyzed oxidative stress in the lower respiratory tract. Ghio et al. (2006) reported that a ferruginous body, with its accumulated iron, functions as an indicator of both metal accumulation and as a potential oxidative stressor\textsuperscript{36}. The clinical presentations of 15 cases were carbonaceous and originated from the lung were observed to persist in patients heavily exposed to textile sprays, symptoms were consistent with a chronic fibrotic disease of the lung, in which there were areas of traction bronchiectasis with chronic inflammation and bronchial metaplasia and bronchiolitis with mixed lymphocytic and eosinophilic infiltration. Staining of resected tissue for iron revealed structures having the appearance of ferruginous bodies. Energy dispersive X-ray analysis and scanning electron microscopy revealed that the fibers isolated from the lung were carbonaceous and originated from the mill. Thus, metal, particularly iron, may play a role in the pathogenesis of Flock Worker’s Lung.

Besides synthetic fibers, textile paints may affect human health in these industries. An outbreak of severe respiratory disease called “Ardystil syndrome” occurred in the Community of Valencia, Spain, among factory workers who worked where textiles were air-sprayed with dyes by using the Acramin F paint system. Twenty-two cases of OP were identified, and of the 22 patients, 6 died within a few months\textsuperscript{37}. Besides OP, interstitial fibrosis and DAD were evident\textsuperscript{38}. In another study, after a 1 year follow-up of 27 patients heavily exposed to textile sprays, symptoms were observed to persist in 15 cases\textsuperscript{39}. The main polycationic components of textile sprays are Acramin FWR (a polyurea), Acramin FWN (a polycrylamide-amine) and Acrafix FH2 (a polyamine), and the non-polycationic component is Acramoll W. Acramin FWR, Acramin FWN and Acrafix FH2 exhibited considerable toxicity in rat and human type II pneumocytes and alveolar macrophages, while Acramoll W was almost nontoxic\textsuperscript{40}. Consistent with the results of \textit{in vitro} experiments, lung damage was caused by Acramin FWR, Acramin FWN, Acrafix FH2 or their mixture after intratracheal instillation in hamsters\textsuperscript{41}. Protein concentration, lactate dehydrogenase (LDH) activity, inflammatory cell number and percentage of polymorphonuclear neutrophils were increased in BAL fluid during the first week, and lung weight remained high for at least a month after intratracheal instillation. Inflammation cell infiltration and subsequent fibrosis with collagen deposition were detected in lung histology, which was confirmed by increased hydroxyproline content in dried lung tissue. Acramoll W did not show toxic effects even \textit{in vivo}. Interestingly, multiple positive charges might play an important role in the toxicity mechanism of the polycations with no irritant properties, since the cytotoxicities decreased in the presence of polyanions\textsuperscript{42}. Overall, combined exposures to textile dyes and nylon flock could be involved in development of the diseases, and cross-talk between them should be further investigated.

**PVC**

PVC is the second most commonly used plastic material worldwide, and it is used in numerous products, e.g., credit cards, computer keyboards, flooring material, food containers, medical cannulae, telephones, highway sound barriers and toys. At the end of the synthesis process, the material may exist as respirable dust, the inhalation of which may result in lung function impairment. Epidemiological surveys have identified PVC dust as an etiologic agent in dyspnea with decreased pulmonary function and appearance of opacities in chest radiograph\textsuperscript{43}, in a particular type of pulmonary fibrosis with a granulomatous reaction\textsuperscript{44} and in interstitial fibrosing pneumonia\textsuperscript{45}. Electron microscopy revealed a nonhomogenous material in the cytoplasm of giant multinucleated cells and/or alveolar macrophages, which was identified to be PVC particles\textsuperscript{44,46,47}. Human alveolar macrophages that engulfed PVC powder showed a similar ultrastructural appearance\textsuperscript{46}. It is important to note that early PVC pneumoconiosis may regress in human cases\textsuperscript{48}.

Several studies on PVC exposure to animals have been conducted, although there is no evidence of fibroprogression in the lung. Rats, guinea pigs and monkeys were exposed by inhalation (6 hours per day, 5 days per week) for 22 months; autopsies of rats and guinea pigs and of monkeys were performed after 12 and 22 months of exposure, respectively. PVC particles were found in aggregated alveolar macrophages, but there were no other effects either on lung histology or pulmonary function\textsuperscript{49}. Hoet and his colleagues have conducted detailed investigations of the effects of PVC exposure \textit{in vitro} and \textit{in vivo}. Emulsion of PVC particles with a mean diameter of 2 µm exhibited moderate toxicity in cultures of different pulmonary cells, i.e., rat and human alveolar macrophages, rat type II pneumocytes, A549 cells (type I cell type) and THP-1 cells (macrophage-like). It was found that the cytotoxicity and inflammatory potential of some PVC particles might be mostly due to their residual additives, since removal of the residual additives considerably reduced their toxic effects\textsuperscript{50}. However, \textit{in vivo} experiments did not confirm the conclusion from the \textit{in vitro} toxicity tests. Male Wistar rats received a single intratracheal instillation of the washed “additive-free” PVC particles. As a result, they exhibited pulmonary inflammation and damage similar to that in the silica-exposed rats at 2 days; how-
ever, at 90 days, most parameters returned to the control level, except for minor histopathological lesions. Interestingly, additive-free PVC particles caused less neutrophil but more eosinophil influx than the original PVC particles containing residual detergents. The washed additive-free PVC particles might be more hydrophobic than the original PVC particles, but pulmonary eosinophilia was induced via an unknown mechanism\textsuperscript{51}. Repeated intratracheal instillation of PVC particles for 3 weeks increased the number of CD4\textsuperscript{+} and CD8\textsuperscript{+} T cells in BAL fluid, and compared with the original PVC particles, the additive-free PVC particles tended to induce more changes in many endpoints, including BAL eosinophilia\textsuperscript{52}, as observed in the single intratracheal instillation study\textsuperscript{51}. Experimental BAL eosinophilia is apparently linked to asthma, as reported in epidemiological studies on PVC\textsuperscript{53,54}. Together, deposition of PVC particles with or without residual detergents in alveolar macrophages and subsequent immunoreactions may contribute to the development of PVC-induced pneumoconiosis.

**DDAC**

DDAC \[[C_{10}H_{22}N(CH_{3})_{2}C_{14}H_{27}:Cl]\], a representative dialkyl quaternary ammonium compound (QAC), is used as a detergent in wood preservatives, as a disinfectant against pathogens and in other applications\textsuperscript{55–58}. DDAC formulations are directly added to water in swimming pools, spas and humidifiers and used for treatment of surfaces in institutional, commercial, industrial and residential settings by fogging, flooding, immersion, wiping, mopping, aerosol spray treatment and low- and high-pressure spray treatments with final spray concentrations ranging from 0.5 to 26320 ppm\textsuperscript{59}. The action of DDAC on the cell membrane causes leakage of intracellular molecules\textsuperscript{60}, together with autolysis and subsequent death of *Escherichia coli* and *Staphylococcus aureus*\textsuperscript{61}. Occupational exposure to QACs, including DDAC, therefore, is known to cause contact dermatitis, conjunctivitis\textsuperscript{62} and asthma\textsuperscript{63–65} among professionals working in healthcare and cleaning industries. Although DDAC does not seem to contaminate the indoor hospital atmosphere during the disinfection process, it can contaminate working atmospheres if it is put in suspension by aerosolization. During the disinfection process, it can contaminate working atmospheres if it is put in suspension by aerosolization, but pulmonary eosinophilia was induced via an unknown mechanism\textsuperscript{51}. Repeated intratracheal instillation of PVC particles for 3 weeks increased the number of CD4\textsuperscript{+} and CD8\textsuperscript{+} T cells in BAL fluid, and compared with the original PVC particles, the additive-free PVC particles tended to induce more changes in many endpoints, including BAL eosinophilia\textsuperscript{52}, as observed in the single intratracheal instillation study\textsuperscript{51}. Experimental BAL eosinophilia is apparently linked to asthma, as reported in epidemiological studies on PVC\textsuperscript{53,54}. Together, deposition of PVC particles with or without residual detergents in alveolar macrophages and subsequent immunoreactions may contribute to the development of PVC-induced pneumoconiosis.

**Molecular Targets Involved in the Pathogenesis of Pulmonary Fibrosis**

**Chemokines and CCRs**

Inflammatory reactions, involving an influx of particular cell types expressing cytokines, chemokines and cell surface molecules, precede and accompany pulmonary fibrosis, whereas nonspecific inflammatory processes end with nonfibrous tissue repair\textsuperscript{78}. Several cytokines and chemokines and their receptors have been investigated with regard to their contribution to the pathogenesis of pulmonary...
fibrosis in human and animal models. Murine MCP-1, also known as JE or chemokine (C–C motif) ligand 2 (CCL2), is considered homologous to human CCL2, which is produced by a variety of cells, including endothelial cells, fibroblasts, monocytes, and smooth muscle cells. MCP-1 and its receptor CCR2 are involved in fibrosis via regulation of profibrotic cytokine generation and ECM formation. This is supported by the fact that CCR2-knockout mice with FITC- or bleomycin-induced pulmonary fibrosis showed improvement in fibrosis. The protective effect was associated with suppressed macrophage infiltration and macrophage-derived MMP production and enhanced alveolar epithelial cell inhibition of fibroblast proliferation. CCR2 also mediates neutrophil recruitment through effects on intravascular adherence and subsequent transmigration. Surprisingly, MCP-1 binds not only to alveolar macrophages but also to bone marrow-derived fibrocytes, both of which express CCR2. Interestingly, transplant of CCR2+/+ bone marrow cells into CCR2–/– recipients restored recruitment of lung fibrocytes and susceptibility to FITC-induced fibrosis. The study showed that fibrocytes may contribute to fibrogenesis in several ways: (1) fibrocytes may directly contribute to fibrosis by secreting collagen, since the amount of collagen secreted by CCR2+/+ fibrocytes exposed to MCP-1 was greater than that secreted by CCR2–/– fibrocytes; (2) fibrocytes secrete TGF-β1, and thus, CCR2-mediated recruitment of fibrocytes to the lung may serve to activate resident fibroblasts via the secretion of TGF-β1; and (3) fibrocytes may differentiate into effector fibroblasts. Murine MCP-5/CCL12, which is homologous to human CCL2, may have a higher affinity for activated macrophages than MCP-1. Moore et al. (2006) proposed that MCP-5 rather than MCP-1 is more likely to drive fibroproliferation in mice via its interaction with CCR2. Inconsistent with this, Tsou et al. (2007) demonstrated that MCP-1 and MCP-3, rather than MCP-2 and MCP-5, are the CCR2 agonists that are most critical for the maintenance of monocytes. Thus, although the contribution of CCR2 agonists remains controversial, the MCP/CCR2 system may represent the link between the macrophage-dominant phase and the subsequent remodeling phase.

CCR1 is constitutively expressed on monocytes, neu-
trophils, lymphocytes and eosinophils and interacts with MIP-1α, RANTES, MCP-2 and MCP-3. After bleomycin challenge in mice, CCR1 mRNA levels and CCR1-positive cells increased and peaked on day 7, which paralleled the expression of MIP-1α and RANTES. Anti-CCR1 antibody inhibited inflammatory cell accumulation and collagen deposition, resulting in dramatic improvement in survival. In contrast, bleomycin-induced an increase in intrapulmonary macrophage and fibrocyte numbers, and collagen deposition was attenuated in MIP-1α−/− mice but not in CCR1−/− mice. CCR1 was observed to play a limited role in pulmonary granuloma formation, since the granuloma size remained unchanged in CCR1−/− mice, as compared with CCR1+/+ mice, challenged with Sepharose beads coupled to the purified protein derivative of Mycobacterium bovis or soluble antigens derived from Schistosoma mansoni eggs. However, natural killer (NK) cell recruitment including CD4+ T cells, CD8+ T cells, NK cells, macrophages and neutrophils, and its ligand is eotaxin-1/CCL11, seemed to be critical in immune-mediated fibrotic disease, and this was supported by the fact that airway remodeling, e.g., goblet cell production and subepithelial fibrosis, was absent in CCR1−/− mice during chronic fungal allergic airway disease. Rather than CCR1, CCR5, another receptor of MIP-1α, seemed to be critical in regulating fibrosis, since CCR5−/− mice showed attenuation of collagen deposition and macrophage infiltration induced by bleomycin.

CCR3 is highly expressed on neutrophils and eosinophils, and its ligand is eotaxin-1/CCL11. Administration of bleomycin induces a marked pulmonary expression of eotaxin-1 and CCR3. Eotaxin-1−/− mice showed reduced pulmonary fibrosis associated with a decrease in TGF-β1 mRNA expression, whereas increased expression of eotaxin-1 by using eotaxin-1-expressing adenovirus enhanced bleomycin-induced lung fibrosis. Similar to eotaxin-1−/− mice, those treated with neutralizing CCR3 antibodies showed reduced pulmonary fibrosis, eosinophilia, neutrophilia and TGF-β1 mRNA expression.

CCR4 is a selective marker for Th2 lymphocytes and is expressed in dendritic cells, NK cells and monocytes; thymus- and activation-regulated chemokine (TARC)/CCL17 and macrophage-derived chemokine (MDC)/CCL22 are both high-affinity ligands and high-potency agonists for CCR4. TARC in bleomycin treatment, which was related to alveolar expression of CCR4. Neutralization of TARC, but not MDC, led to a reduction in collagen deposition and BAL leukocytes, including CD4+ T cells, CD8+ T cells, NK cells, macrophages and neutrophils. TARC was expressed in alveolar epithelial cells in the lung tissues of bleomycin-treated mice and human patients with IPF. These data support the results of an experiment conducted using CCR4−/− mice, which protected from bleomycin-induced lethal inflammatory and fibrotic responses, with evidence of a reduction in the TARC and MDC levels observed in lung homogenates. A major contribution to this protective effect might be the regulatory role of CCR4 in determining the phenotype of macrophages during the acute inflammatory phase by switching classically activated or M1 macrophages (type-1 polarization, induced by Th1 signals, i.e., IFN-γ expression) to alternatively activated or M2 macrophages (type-2 polarization, induced by Th2 signals, i.e., IL-4 and IL-13 expression). In the presence of CCR4, TARC and MDC promoted tissue injury through induction of the M1 macrophage phenotype with increased nitric oxide synthase 2 (NOS2) and decreased arginase 1 expression; in the absence of CCR4, M2 macrophage activation occurred through suppression of NOS2 and increased expression of arginase 1 and found in inflammatory zone 1 (FIZZ1), favoring upregulation of a decoy receptor, D6, which attenuates inflammation and tissue injury by internalizing and degrading chemokines. Thus, it appears that alterations in M1/M2 marker expression are confined to the early inflammatory stage and that the establishment of a fibrotic process is not necessarily associated with M2 polarization. Furthermore, reduction in arginase 1 in lung epithelial cells enhanced the levels of NO metabolites and S-nitrosylated proteins and resulted in increased TNF-α or lipopolysaccharide (LPS)-stimulated nuclear factor-κB (NF-κB) DNA binding. Coculture of FIZZ1-expressing type II alveolar epithelial cells with fibroblasts stimulates α-SMA and type I collagen expression independent of TGF-β1 and dependent on Notch/Jagged. The imbalance of arginase and NOS2 in association with the induction of FIZZ1 may contribute to fibrogenesis, depending on the stage of inflammation and specific cell types.

CCR7 is expressed by T and B cells and plays an important role in T cell and dendritic cell trafficking in association with its ligands, Epstein-Barr-induced 1 (EBI1)-ligand chemokine (ELC)/CCL19 and secondary lymphoid-tissue chemokine (SLC)/CCL21. CCR7 expression is raised in a severe form of IIP, UIP, and localized to focal areas consisting of activated resident fibroblasts, rather than myofibroblasts and bone marrow-derived fibrocytes. This was supported by Pierce et al. (2007), who showed that CCR7 is expressed by primary IPF/UIP fibroblasts but not by normal fibroblasts. IPF/UIP fibroblasts showed migration and proliferation in response to CCR7 activation by SLC, but not by ELC, and SLC-mediated CCR7 activation seemed to be limited to the extracellular signal-regulated kinase (ERK) and 90-kDa ribosomal S6 kinase (p90RSK) pathways, since the p58 mitogen-activated protein kinase (MAPK) and c-Jun N-terminal kinase (JNK) pathways were not activated by SLC. The investigators adopted an unusual technique to clarify the role of SLC/CCR7 axis elegantly. IPF/UIP fibroblasts, NSIP fibroblasts and normal fibroblasts were intravenously injected into severe combined immunodeficiency (SCID) mice lacking adaptive and innate immune features. Interestingly, the mice with IPF/UIP fibroblasts showed patchy interstitial fibrosis and those with NSIP fi-
broblasts showed a more diffuse interstitial fibrosis, with an increased hydroxyproline content in both cases. The injected normal fibroblasts did not induce interstitial remodeling. Neutralization of SLC or CCR7 attenuated pulmonary fibrosis in mice that received either type of fibroblasts; the effect was related to an early increase in lung CD4+ T cells and late increase in CD4+CD25+FoxP3+ Treg, which was consistent with increased IL-2 expression107, indicating that CCR7-independent Treg expansion is a novel therapeutic target for pulmonary fibrosis.

Treg

T cells are present in the lungs of patients with pulmonary fibrosis because a variety of causes play a pivotal role in the fibrotic process. CD4+ T cells are abundant in the lung in granulomatous lung diseases such as IPF, sarcoidosis and berylliosis10,13,108. In fact, CD4+ T cells from IPF patients have characteristics typical of cell-mediated pathologic responses, including augmented effector functions (production of TGF-β1, IL-10 and TNF-α), provision of facultative help for immunoglobulin G (IgG) autoantibody production, oligoclonal expansions and proliferations driven by an antigen present in diseased tissues109. Most previous studies investigated whole T cells, while the emerging novel subpopulations of naturally occurring and adaptive Treg take the center stage as the crucial immunoregulatory cells that are capable of suppressing Th1- and Th2-mediated adaptive immune responses in a cell contact-dependent fashion directly or by acting on antigen-presenting cells110. Since the transcription factor Foxp3 has been shown to be selectively expressed in Treg in humans and mice, Foxp3 mRNA represents a more specific marker than cell surface molecules such as CD25, cytotoxic T lymphocyte-associated antigen 4 (CTLA-4) and glucocorticoid-induced TNF receptor (GITR)111–114.

In CBD and beryllium-sensitized patients, a small population of BAL CD4+ T cells retained CD27 expression, and these CD4+CD27+ T cells contained the Foxp3-expressing naturally occurring Treg subset, increasing T cell expansion, while the vast majority of CD4+ T cells had lost surface CD27 expression, which inversely correlated with lung inflammation in the patients115. The number of CD4+CD25+FoxP3+ Treg and their activities (demonstrated by Th1- and Th2-cytokine expression) were reduced in both BAL and peripheral blood of patients with IPF as compared with those of healthy volunteers and patients without IPF; further, the defective function of BAL Treg highly correlated with the parameters of disease severity, as determined by pulmonary function tests116. Furthermore, downregulation of CD28, which induces FoxP3 and generates CD4+CD25+ Treg, was evident in IPF patients, and these patients demonstrated infiltrations of CD4+CD28null T cells in lung tissues and a positive correlation between the presence of these cells and induction of lung transplantation or death in the next year117. Thus, the data suggested that Treg play a pivotal role in pulmonary fibrosis; however, additional studies extensively addressing Treg interactions with cellular and soluble factors in animal models and human patients are required, since it has been reported that Treg depletion accelerates in vitro granuloma growth in mononuclear cell cultures of healthy controls but not in those of patients with active sarcoidosis118.

TGF-β and BMP signaling

TGF-β1 has the ability to induce the expression of ECM proteins in mesenchymal cells119. Cellular TGF-β1 mRNA levels were higher than cellular TGF-β2 and TGF-β3 mRNA levels in IPF patients120 and bleomycin-treated mice121. However, TGF-β2 and TGF-β3 have the potential for in vitro fibrogenic activity that is the same as or higher than the in vitro fibrogenic activity of TGF-β1122. Signaling by TGF-β family members occurs via TGF-β type I and type II receptors (TGF-βRI and TGF-βRII, respectively)119,123,124. Upon phosphorylation by activated TGF-βRI/activin receptor-like kinase-5 (ALK-5), TGF-β-activated Smad2/Smad3 forms a heteromeric complex with Smad4, which is translocated to the nucleus where it functions as a transcription factor. Smad3, in particular, is of critical importance in the development of fibrosis123,124, since loss of Smad3 greatly attenuates histopathological fibrotic responses to bleomycin125 or active TGF-β1-expressing adenovirus126 in the mouse lung. Active TGF-β1 is a major cytokine that stimulates transcription of the ColIα2 gene, as determined by the binding of Smad3-Smad4 complex to the cis-element TGF-β-responsive element (TbRE) in the proximal promoter region127.

It is important to note that repression of collagen gene expression is critical for pulmonary disease therapy, and lately, two complex underlying mechanisms have been proposed by Xu et al. (2006, 2007): methylation-mediated repression may be mediated by interaction of the regulatory factor for X-box 1 (RFX1) and histone deacetylase 1 (HDAC1) at the TATA box, or IFN-γ-mediated repression may be mediated by the interaction of RXF5, class II transactivator, HDAC2, and peroxisome proliferator-activated receptor γ at the CCAAT and TATTA boxes128,130. Lin et al. (2006) identified protein phosphatase 1A (PP1A)/PP2Ca as a Smad2/Smad3 SXS motif-specific phosphatase that inhibits Smad2/Smad3 phosphorylation131. Interestingly, phosphatase and tensin homolog (PTEN) deleted on chromosome 10 plays a negative role in the TGF-β pathway by forming a complex with PP1A/PP2Ca132. A lipid mediator, sphingosine 1-phosphate (SIP), mimics TGF-β-induced cell responses through cross-activation of Smad signaling133 or Rho signaling134 cascades, while dihydrosphingosine 1-phosphate (dSIP) plays an opposite role in the regulation of TGF-β signaling by stimulating phosphorylation of PTEN and its subsequent translocation to the nucleus132. Thus, repression of collagen gene expression and negative
regulation of TGF-β/Smad signaling through formation of a PP1A/PP2Cα-PTEN complex, probably mediated by dS1P, may open the possibilities to control the progression of pulmonary fibrosis.

Further, TGF-β terminates the induction of its own target genes by induction of Smad7, which competes with Smad2 and Smad3 for binding to TGF-βRI125; inhibits receptor-activated Smad2 phosphorylation150; recruits the E3 ubiquitin ligases Smurfl1, Smurfl2, Nedd4-2 and WW domain-containing protein 1 (WWP1)/Tiu1 to TGF-βRI and Smads, causing their degradation136; or specifically binds to the Smad-responsive element via its Mad homology 2 (MH2) domain and disrupts formation of a TGF-β-induced functional Smad-DNA complex137. As expected, a decrease in the expression of Smad7 was observed after bleomycin instillation in rats, in contrast to a persistent increase in the phosphorylation and nuclear localization of Smad2/Smad3138. The same groups compared the levels of phosphorylated Smad3 and Smad7 in isolated fibroblasts from the lungs of control and bleomycin-treated rats under normal conditions and after TGF-β treatment139. The basal levels of phosphorylated Smad3 were higher in the normal lung fibroblasts than in bleomycin-treated lung fibroblasts, but the basal levels of Smad7 were comparable. After TGF-β treatment, the levels of phosphorylated Smad3 and Smad7 mRNA were increased in both treated and normal cells, while the protein level of Smad7 was increased in the normal lung fibroblasts as compared with the bleomycin-
treated lung fibroblasts. The investigators concluded that inadequate response to TGF-β and consequent imbalance between the levels of Smad7 and phosphorylated Smad3 might contribute to the fibrotic phenotype characteristic of activated fibroblasts. In fact, bleomycin-induced collagen deposition and phosphorylation of Smad3 were prevented by an intratracheal injection of a recombinant adenovirus carrying mouse Smad7 cDNA[140]. Intriguingly, inhibition of TGF-β2 release by IFN-γ[141] and myofibroblast differentiation by hepatocyte growth factor (HGF)[142] has been reported to be dependent on Smad7. Overall, overexpression of Smad7 may be a therapeutic target for IIPs.

BMPs, member of one of the TGF-β family, have been investigated in pulmonary vascular disorders, especially pulmonary hypertension, which has been linked to mutations in the BMP receptor II gene[123] and expression of BMP-2 and BMP-4. BMP-2 expression is increased by proinflammatory stimuli and induces endothelial dysfunction, oxidative stress, and endothelial activation, including increased adhesion of a monocyte cell line[143]. BMP-4 promotes migration of vascular smooth muscle cells, possibly contributing to vascular remodeling, i.e., medial wall thickening and muscularization of vessel walls[144]. Lately, the role of BMPs, particularly BMP-7 and BMP-4, and that of gremlin in pulmonary fibrosis has been investigated. BMP-7 is known to act as an antagonist of TGF-β-dependent fibrogenic activity in mouse pulmonary myofibroblasts by inducing inhibitor of differentiation 2[145], which is an important myoepithelial cell marker during epithelial-mesenchymal transition[146,147]. However, the role of BMP-7 in fibrosis remains controversial, since BMP-7 treatment significantly reduced the hydroxyproline content in asbestos-treated mice[148] but not in bleomycin-treated mice[149]. No alterations in BMP-4 levels have been reported in lung samples of IPF patients, but IPF fibroblasts are less responsive to exogenous BMP-4, which inhibits the growth of and induces apoptosis in myofibroblasts[20]. However, BMP-4 and BMP-7 accurately regulate fibrogenesis in different ways: BMP-4, but not BMP-7, reduces TGF-β1-induced ECM production, while BMP-7, but not BMP-4, inhibits TGF-β1-induced myofibroblast transformation in normal human lung fibroblasts[150]. On the other hand, TGF-β1 induces the expression of a BMP inhibitor, gremlin, in A549 lung epithelial cells, and IPF fibroblasts and their lung samples show high levels of gremlin mRNA and protein[152,154]. Pulmonary gremlin mRNA levels were also upregulated in asbestos-treated mice[152]. Increased gremlin level may decrease BMP-4-mediated myofibroblast apoptosis and increase TGF-β signaling through suppression of BMP signaling. This concept was supported by evidence of latent TGF-β-binding protein-4−/− fibroblasts, which exhibited reduced activation of TGF-β due to increased expression of BMP-4 and decreased expression of gremlin[151]. Thus, profibrotic and antiﬁbrogenic signaling regulated by TGF-β and BMPs and the role of gremlin in disrupting the balance between both the mediators provides the complex feedback loop coordinating fibrogenesis[152].

Conclusion

The mechanism by which cytotoxicity and inflammation cause fibrosis in the lung in response to environmental cues is not fully understood. In most pulmonary fibrotic conditions, cytotoxicity, inflammation and repair could be dysregulated by imbalance in the production of chemokines, cytokines and growth factors, and pulmonary wound repair is an extremely dynamic process intersecting immunology, structural biology and airway physiology[153]. When a cytotoxic effect is minimal or self-limited, repair would proceed to restore the normal structure, but when an injury is more extensive, tissue repair might result in scarring and/or fibrosis[154]. The significance of new discoveries in understanding the pathogenesis of diseases and the potential molecular targets involved in advancing or interfering with fibrogenesis continues to be evaluated using in vivo analyses of animal models substituting for patients with ILDs/DPLDs[155]. Important advances have been made in identifying molecules that are able to inhibit or induce lung granulomas and fibrosis, including TGF-β and BMP signaling and chemokines and their receptors in relation to reduction in Treg (Fig. 2). Evidence by toxicological approaches would be expected to explore new aspects of the pulmonary diseases. Exposure to beryllium causes a Th1 cytokine (TNF-α, IFN-γ and IL-2)-dominant granulomatous process, which might share the features of sarcoidosis, a more frequent disorder with similar pathological features[156,157]. Discovering the role of Treg in CBD provides new insights in the mechanism of development of granulomatous lesions. On the other hand, nongranulomatous fibrosis has been found in nylon flock-exposed individuals, with or without textile paint exposure, although experimental data are quite limited as of 2010. PVC is known to be an etiologic agent of pneumoconiosis, including granulomatous or nongranulomatous fibrosis, and of lung cancer, hepatic angiosarcoma and leukemia/lymphoma[158]. QACs, including DDAC, may cause pulmonary diseases such as asthma or fibrosis, as shown by etiological research[63–65] and our experimental study[69]. Because there are several types of ILDs/DPLDs (Table 1), there should be a note of caution regarding the pathological characteristics in human and animal cases.

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