Mediators of Chronic Obstructive Pulmonary Disease

PETER J. BARNES

National Heart and Lung Institute, Imperial College, London, United Kingdom

Abstract

I. Introduction

II. Chronic obstructive pulmonary disease as an inflammatory disease

A. What is chronic obstructive pulmonary disease?

B. Differences from asthma

C. Inflammatory cells

1. Neutrophils

2. Macrophages

3. T Lymphocytes

4. Eosinophils

5. Dendritic cells

6. Epithelial cells

III. Lipid mediators

A. Prostanoids

1. Prostaglandin E\(_2\)

2. Prostaglandin F\(_2\alpha\)

3. Thromboxane

B. Leukotrienes

1. Leukotriene B\(_4\)

2. Cysteinyl-leukotrienes

C. Platelet-activating factor

IV. Reactive oxygen species

A. Formation

B. Antioxidants

C. Evidence for increased oxidative stress

1. Pulmonary oxidative stress

2. Exhaled markers of oxidative stress

3. Systemic markers of oxidative stress

D. Effects on airway function

1. Effects on transcription factors

2. Effects on signal transduction pathways

3. Effects on target cells

4. Effects on inflammatory response

5. Effect on proteases

6. Effect on steroid responsiveness

7. Effects on apoptosis

8. Systemic effects

E. Effects of antioxidants

V. Nitric oxide

A. Formation

1. Nitric oxide

2. Peroxynitrite

B. Inhibition

Address correspondence to: P. J. Barnes, National Heart and Lung Institute, Imperial College School of Medicine, Dovehouse St, London SW3 6LY, United Kingdom. E-mail: p.j.barnes@imperial.ac.uk

Article, publication date, and citation information can be found at http://pharmrev.aspetjournals.org.
doi:10.1124/pr.56.4.2.
VI. Peptide mediators ................................................................. 529
  A. Endothelins ..................................................................... 529
    1. Formation .................................................................. 529
    2. Effects ....................................................................... 529
    3. Therapeutic potential .................................................. 529
  B. Bradykinin .................................................................... 529
  C. Tachykinins .................................................................. 529
    1. Formation .................................................................... 529
    2. Effects ....................................................................... 529
    3. Therapeutic potential .................................................. 530
  D. Complement fragments .................................................... 530

VII. Chemokines ..................................................................... 530
  A. Interleukin-8 .................................................................. 530
    1. Formation .................................................................... 530
    2. Effects ....................................................................... 531
    3. Therapeutic potential .................................................. 531
  B. Growth-related onco gene–α .............................................. 531
  C. Epithelial cell-derived neutrophil activating protein–78 . ........................................................................ 532
  D. CX3 chemokines .............................................................. 532
    E. Monocyte chemoattractant protein–1 ................................ 533
      1. Production in chronic obstructive pulmonary disease ................................................................. 533
      2. Effects in chronic obstructive pulmonary disease ........................................................................ 533
    F. Macrophage inflammatory protein .................................. 533
    G. Eosinophil-selective chemokines .................................... 533
    H. Lymphocyte-selective chemokines .................................. 533
    I. Dendritic cell-selective chemokines ................................. 534
    J. CX3C chemokines .......................................................... 534

VIII. Cytokines ....................................................................... 534
  A. Tumor necrosis factor–α ................................................... 534
    1. Increased production .................................................... 534
    2. Effects ........................................................................ 534
    3. Inhibition ..................................................................... 535
  B. Interleukin–1β ................................................................ 535
  C. Interleukin–6 .................................................................. 535
  D. Interleukin–9 .................................................................. 535
  E. Granulocyte–macrophage colony stimulating factor ............. 536
  F. Interleukin–10 ................................................................. 536
  G. Interleukin–12 ................................................................ 536
  H. Interleukin–13 ................................................................ 536
  I. Interleukin–17 ................................................................. 536
  J. Interferon–γ ................................................................. 536

IX. Growth factors .................................................................. 536
  A. Transforming growth factors ............................................ 536
  B. Epidermal growth factor .................................................. 537
  C. Vascular-endothelial growth factor .................................... 537
  D. Fibroblast growth factors .................................................. 538

X. Proteases ........................................................................ 538
  A. Neutrophil elastase .......................................................... 538
  B. Other serine proteases ..................................................... 539
  C. Cysteine proteases ............................................................ 539
  D. Matrix metalloproteinases .................................................. 539
  E. Antiproteases ................................................................ 540
    1. α1-Antitrypsin .............................................................. 540
    2. Secretory leukoprotease inhibitor .................................... 540
    3. Tissue inhibitor of matrix metalloproteinases ................. 540
Abstract—Chronic obstructive pulmonary disease (COPD) is a major and increasing global health problem that is now a leading cause of death. COPD is associated with a chronic inflammatory response, predominantly in small airways and lung parenchyma, which is characterized by increased numbers of macrophages, neutrophils, and T lymphocytes. The inflammatory mediators involved in COPD have not been clearly defined, in contrast to asthma, but it is now apparent that many lipid mediators, inflammatory peptides, reactive oxygen and nitrogen species, chemokines, cytokines, and growth factors are involved in orchestrating the complex inflammatory process that results in small airway fibrosis and alveolar destruction. Many proteases are also involved in the inflammatory process and are responsible for the destruction of elastin fibers in the lung parenchyma, which is the hallmark of emphysema. The identification of inflammatory mediators and understanding their interactions is important for the development of anti-inflammatory treatments for this important disease.

I. Introduction

Chronic obstructive pulmonary disease (COPD) is a major and increasing global health problem. It is predicted by the World Health Organization to become the third most common cause of death and the fifth most common cause of disability in the world by 2020 (Lopez and Murray, 1998). Indeed, COPD is already the fourth most common cause of death and the only common cause of death in the United States that has increased over the last 30 years (Murray et al., 2001). Although there have been major advances in the understanding and management of asthma, COPD has been relatively neglected, and there are no current therapies that reduce the inevitable progression of this disease. However, because of the enormous burden of disease and escalating health care costs, which now exceed those of asthma by more than 3-fold, there is now renewed interest in the understanding of inflammatory mediators and the role of mediators in the disease (Barnes, 2000a) and a search for new therapies (Barnes, 2001c), resulting in a reevaluation of the disease (Barnes, 2002b, 2003).

Although many inflammatory mediators (now more than 100) have been identified in asthma (Barnes et al., 1998; Chung and Barnes, 1999), there is much less information about the production and role of mediators in COPD. COPD is a complex inflammatory disease that involves many different types of inflammatory and structural cells, all of which have the capacity to release multiple inflammatory mediators (Figs. 1 and 2). This suggests that mediator antagonists may have some potential as new therapies for COPD. However, because of the redundant effects of many inflammatory mediators, it is unlikely that antagonism of a single mediator will provide major clinical benefit, as is the case in asthma. Although asthma and COPD both involve chronic inflammation in the respiratory tract, there are marked differences in the types of inflammatory cells involved and in the site of inflammation, making it likely that different patterns of mediators are involved. There is much less information available about the mediators of COPD than those of asthma. Unlike asthma, some patients with COPD also have systemic features of the disease, and these are also likely to be mediated via inflammatory mediators.

II. Chronic Obstructive Pulmonary Disease as an Inflammatory Disease

A. What is Chronic Obstructive Pulmonary Disease?

COPD is characterized by slowly progressive development of airflow limitation that is poorly reversible, in sharp contrast to asthma where there is variable airflow obstruction that is usually reversible spontaneously or with treatment. A new definition of COPD has recently been adopted by the Global Initiative on Obstructive Lung Disease: “a disease state characterized by airflow limitation that is not fully reversible. The airflow limi-
Inflammatory mechanisms in COPD. Cigarette smoke (and other irritants) activate macrophages in the respiratory tract that release neutrophil chemotactic factors, including IL-8 and LTβ1. These cells then release proteases that break down connective tissue in the lung parenchyma, resulting in emphysema, and also stimulate mucus hypersecretion. These enzymes are normally counteracted by protease inhibitors, including α1-antitrypsin, SLPI, and TIMP. Cytotoxic T cells (CD8+T) may also be recruited and may be involved in alveolar wall destruction. Fibroblasts may be activated by growth factors released from macrophages and epithelial cells. CTG, connective tissue growth factor; COB, chronic obstructive bronchiolitis.

Inflammation in COPD is complex, with many activated inflammatory and structural cells that release multiple mediators, including lipid mediators such as LTβ1, which is chemoattractant for neutrophils; chemokines such as MCP-1 and MIP-1α, which attract monocytes; IL-8 and GRO-a, which attract neutrophils and monocytes; IP-10, which attracts CD8+ T cells; ROS, and NO; GM-CSF, which prolongs neutrophils' survival; TNF-α, which amplifies inflammation by switching on multiple inflammatory genes and may also account for some of the systemic effects of the disease; and endothelin and TGF-β, which induce fibrosis. In addition, multiple proteases are released that result in elastolysis, including the serine proteases neutrophil elastase and proteinase C, cathepsins, and MMPs. This combination of mediators that attract and activate inflammatory cells and proteinases, which cause elastolysis and mucus hypersecretion, results in the typical pathophysiology of COPD.

Inflammation is usually progressive and associated with an abnormal inflammatory response of the lungs to noxious particles and gases" (www.goldcopd.com/workshop/index.html). For the first time, this definition encompasses the idea that COPD is a chronic inflammatory disease, and much of the recent research has focused on the nature of this inflammatory response.

COPD includes chronic obstructive bronchitis with fibrosis and obstruction of small airways, and emphysema with enlargement of airspaces and destruction of lung parenchyma, loss of lung elasticity, and closure of small airways (Fig. 3). The obstruction of peripheral airways due to inflammatory cell infiltration and fibrosis, together with inflammatory exudates in the lumen, correlate best with the severity of airflow obstruction, indicating the importance of chronic inflammation in COPD (Hogg et al., 2004). Chronic bronchitis, by contrast, is defined by a productive cough of more than 3 months’ duration for more than two successive years; this reflects mucus hypersecretion and is not necessarily associated with airflow limitation. Most patients with COPD have all three pathological mechanisms (chronic obstructive bronchitis, emphysema, and mucus plugging) as all are induced by smoking, but they may differ.
in the proportion of emphysema and obstructive bronchitis. In developed countries, cigarette smoking is by far the most common cause of COPD, but there are several other risk factors, including air pollution (particularly indoor air pollution from burning fuels), poor diet, and occupational exposure. COPD is characterized by acceleration in the normal decline of lung function seen with age (Fig. 4). The slowly progressive airflow limitation leads to disability and premature death and is quite different from the variable airway obstruction and symptoms in asthma, which rarely progresses in severity.

**B. Differences from Asthma**

Although COPD and asthma both involve inflammation in the respiratory tract, there are marked differences in the nature of the inflammatory process, with differences in inflammatory cells, mediators, response to inflammation, anatomical distribution, and response to anti-inflammatory therapy (Barnes, 2000b; Saetta et al., 2001) (Fig. 5). Some patients appear to share the characteristics of COPD and asthma, however. Rather than this representing a graded spectrum of disease, it is more likely that these patients have both of these common diseases at the same time.

Histopathological studies show a predominant involvement of peripheral airways (bronchioles) and lung parenchyma, whereas asthma involves inflammation in all airways but without involvement of the lung parenchyma. There is obstruction of bronchioles, with fibrosis and infiltration with macrophages and T lymphocytes. There is destruction of lung parenchyma, as well as an increased number of macrophages and CD8+ (cytotoxic) T lymphocytes (Saetta et al., 1998). Bronchoalveolar lavage (BAL) fluid and induced sputum demonstrate a marked increase in macrophages and neutrophils (Keatings et al., 1996; Pesci et al., 1998). In contrast to asthma, eosinophils are not prominent except during exacerbations or when patients have concomitant asthma (Fabbri et al., 1998, 2003).

**C. Inflammatory Cells**

COPD is a complex inflammatory disease that involves several types of inflammatory cells (Barnes et al., 2003). Although abnormal numbers of inflammatory
cells have been documented in COPD, the relationship between these cell types and the sequence of their appearance and their persistence are largely unknown. Most studies have been cross-sectional based on selection of patients with different stages of the disease, and comparisons have been made between smokers without airflow limitation (normal smokers) and those with COPD who have smoked a similar amount. There are no serial studies, and selection biases (such as selecting tissue from patients suitable for lung volume reduction surgery) may give misleading results. Analysis of the cell profile in alveoli and small airways shows an increase in all of the cell types implicated in COPD, including macrophages, T lymphocytes, B lymphocytes, and neutrophils (Retamales et al., 2001).

1. Neutrophils. Increased numbers of activated neutrophils are found in sputum and BAL fluid of patients with COPD (Lacoste et al., 1993; Keatings et al., 1996), yet they are increased relatively little in the airways or lung parenchyma (Finkelstein et al., 1995). This may reflect their rapid transit through the airways and parenchyma. Neutrophils secrete serine proteases, including neutrophil elastase (NE), cathepsin G, and proteinase-3, as well as matrix metalloproteinase (MMP)-8 and MMP-9, which may contribute to alveolar destruction. These serine proteases are also potent mucus stimulants. Neutrophil recruitment to the airways and parenchyma involves adhesion to endothelial cells, and E-selectin is up-regulated on endothelial cells in the airways of COPD patients (Di Stefano et al., 1994). Adherent neutrophils then migrate into the respiratory tract under the direction of neutrophil chemotactic factors, which include interleukin (IL)-8 and leukotriene B₄ (LTB₄). Neutrophil survival in the respiratory tract may be increased by cytokines, such as granulocyte-macrophage colony stimulating factor (GM-CSF) and granulocyte colony stimulating factor.

The role of neutrophils in COPD is not yet clear. There is a correlation between the number of circulating neutrophils and fall in forced expiratory volume in 1 s (FEV₁) (Sparrow et al., 1984). Neutrophil numbers in bronchial biopsies and induced sputum are correlated with COPD disease severity (Keatings et al., 1996; Di Stefano et al., 1998) and with the rate of decline in lung function (Stanescu et al., 1996). Smoking has a direct stimulatory effect on granulocyte production and release from the bone marrow, possibly mediated by GM-CSF and granulocyte colony stimulating factor released from lung macrophages (Terashima et al., 1997). Smoking may also increase neutrophil retention in the lung (MacNee et al., 1989). There is no doubt that the neutrophils recruited to the airways of COPD patients are activated, since there are increased concentrations of granule proteins, such as myeloperoxidase and human neutrophil lipocalin, in the sputum supernatant (Keatings and Barnes, 1997; Yamamoto et al., 1997; Peleman et al., 1999). These neutrophils also show an increase in the respiratory burst response, which correlates with the degree of airflow limitation (Richards et al., 1989).
Neutrophils have the capacity to induce tissue damage through the release of serine proteases and oxidants. Priming is a prerequisite for degranulation and superoxide anion generation in neutrophils (Condliffe et al., 1998). Neutrophils in the peripheral circulation show evidence of priming in COPD (Noguera et al., 2001), but this may result from, rather than contribute to, lung pathophysiology. There are several chemotactic signals that have the potential for neutrophil recruitment in COPD, including LTB4, IL-8, and related CXC chemokines, which are increased in COPD airways (Tanino et al., 2002; Traves et al., 2002). These mediators may be derived from alveolar macrophages and epithelial cells, but the neutrophil itself is a major source of IL-8 (Bazzoni et al., 1991).

Neutrophils from the circulation marginate in the pulmonary circulation and adhere to endothelial cells in the alveolar wall before passing into the alveolar space (Hogg and Walker, 1995). The precise route for neutrophil migration in large airways is less certain, but it is more likely that they reach the airway from the tracheobronchial circulation and migrate across postcapillary venules (Pettersen and Adler, 2002). The cellular mechanisms underlying neutrophil adhesion and transmigration differ between systemic and pulmonary circulations, and this might confer different properties on the neutrophils arriving from the alveolar or bronchial compartments. There may be significant differences in neutrophil transit times in different areas of the lung that may account for differential distribution of emphysema, for example, the upper lobe predominance in centrilobular emphysema. Little is known about survival and apoptosis of neutrophils in COPD airways. Theoretically, GM-CSF may prolong neutrophil survival, but it has proven difficult to culture neutrophils from sputum samples.

However, although neutrophils have the capacity to cause elastolysis, this is not a prominent feature of other pulmonary diseases where chronic airway neutrophilia is even more prominent, including cystic fibrosis and bronchiectasis. This suggests that other factors are involved in the generation of emphysema. Indeed, there is a negative association between the number of neutrophils and the amount of alveolar destruction in COPD (Finkelstein et al., 1995), and neutrophils are not a prominent feature of parenchymal inflammation in COPD. However, it is likely that airway neutrophilia is linked to mucus hypersecretion in chronic bronchitis. Serine proteases from neutrophils, including neutrophil elastase, cathepsin G, and proteinase-3, are all potent stimulants of mucus secretion from submucosal glands and goblet cells in the epithelium (Sommerhoff et al., 1990; Witko-Sarsat et al., 1999).

2. Macrophages. Macrophages appear to play a pivotal role in the pathophysiology of COPD and can account for most of the known features of the disease (Shapiro, 1999; Barnes, 2004) (Fig. 6).

There is a marked increase (5- to 10-fold) in the numbers of macrophages in airways, lung parenchyma, BAL fluid, and sputum in patients with COPD. A careful morphometric analysis of macrophage numbers in the parenchyma of patients with emphysema showed a 25-fold increase in the numbers of macrophages in the tissue and alveolar space compared with normal smokers (Retamales et al., 2001). Furthermore, macrophages are localized to sites of alveolar wall destruction in pa-
tients with emphysema (Finkelstein et al., 1995; Mishi et al., 2002). There is a correlation between macrophage numbers in the airways and the severity of COPD (Di Stefano et al., 1998).

Macrophages may be activated by cigarette smoke extract to release inflammatory mediators, providing a cellular mechanism that links smoking with inflammation in COPD. Alveolar macrophages also secrete elastolytic enzymes, including MMP-2, MMP-9, MMP-12, cathepsins K, L, and S, and neutrophil elastase taken up from neutrophils (Punturieri et al., 2000; Russell et al., 2002b). Alveolar macrophages from patients with COPD secrete more inflammatory proteins and have a greater elastolytic activity at baseline than those from normal smokers, and this is further increased by exposure to cigarette smoke (Lim et al., 2000b; Russell et al., 2002a, b). Macrophages demonstrate this difference even when maintained in culture for 3 days and therefore appear to be intrinsically different from the macrophages of normal smokers and nonsmoking normal control subjects (Russell et al., 2002b). The predominant elastolytic enzyme secreted by alveolar macrophages in COPD patients is MMP-9. Most of the inflammatory proteins that are up-regulated in COPD macrophages are regulated by the transcription factor nuclear factor-κB (NF-κB), which is activated in alveolar macrophages of COPD patients, particularly during exacerbations (Di Stefano et al., 2002; Caramori et al., 2003).

The increased numbers of macrophages in smokers and COPD patients may be due to increased recruitment of monocytes from the circulation in response to monocyte-selective chemokines and T lymphocytes via the release of lymphocyte chemotactic factors. The increased numbers of macrophages in COPD may also be due to increased proliferation and prolonged survival in the lungs. Macrophages have a very low proliferation rate in the lungs, but we have demonstrated that there is some increase in cell proliferation measured by proliferative cell nuclear antigen (Tomita et al., 2002). Macrophages have a long survival time, so this is difficult to measure directly. However, in macrophages from smokers, there is markedly increased expression of the antiapoptotic protein Bcl-XL and increased expression of p21<sup>WAF1</sup> in the cytoplasm (Tomita et al., 2002). This suggests that macrophages may have a prolonged survival in smokers and patients with COPD.

Corticosteroids are ineffective in suppressing inflammation, including cytokines, chemokines, and proteases, in patients with COPD (Keatings et al., 1997; Culpitt et al., 1999). In vitro the release of IL-8, TNF-α, and MMP-9 macrophages from normal subjects and normal smokers are inhibited by corticosteroids, whereas corticosteroids are ineffective in macrophages from patients with COPD (Culpitt et al., 2003). Curiously, this does not apply to GM-CSF, which does not appear to have increased secretion in COPD and is suppressed by corticosteroids, albeit to a lesser extent than in macrophages from normal smokers. The reasons for resistance to corticosteroids in COPD and, to a lesser extent, macrophages from smokers may be the marked reduction in activity of histone deacetylase (HDAC) (Ito et al., 2001a), which is recruited to activated inflammatory genes by glucocorticoid receptors to switch off inflammatory genes (Ito et al., 2000). The reduction in HDAC activity in macrophages is correlated with increased secretion of cytokines like TNF-α and IL-8 and reduced response to corticosteroids. The reduction of HDAC activity on COPD patients may be mediated through oxidative stress and peroxynitrite formation.

Macrophages are phagocytic for bacteria and play an important role in host defense. The phagocytic potential of macrophages from COPD patients has not been explored, but it is possible that impaired phagocytosis may result in the increased bacterial load in the respiratory tract of patients with COPD. Macrophages recognize apoptotic cells via expression of macrophage-activating factor, which interacts with specific receptors on the macrophage surface (Fadok et al., 2000). Ingestion of apoptotic granulocytes by macrophages induces the secretion of transforming growth factor (TGF)-β1 (Huynh et al., 2002). Neutrophil elastase cleaves the phosphatidylserine receptor and may thus impair the ability of macrophages to take up apoptotic neutrophils, resulting in increased numbers of apoptotic neutrophils in the airways (Vandivier et al., 2002).

3. T Lymphocytes. There is an increase in the total numbers of T lymphocytes in lung parenchyma and peripheral and central airways of patients with COPD, with the greater increase in CD8<sup>+</sup> than in CD4<sup>+</sup> cells (Finkelstein et al., 1995; O'Shaughnessy et al., 1997; Saetta et al., 1999; Majo et al., 2001; Retamales et al., 2001). There is a correlation among the number of T cells, the amount of alveolar destruction, and the severity of airflow obstruction. There is also an increase in the absolute number of CD4<sup>+</sup> T cells, but the ratio of CD4<sup>+</sup>/CD8<sup>+</sup> cells is reversed in COPD. This is mainly found in smokers with COPD rather than smokers without evidence of airflow limitation (Majo et al., 2001). It is not known whether these cells are classified as Tc1 (interferon-γ producing) or Tc2 (IL-4 producing) subtypes (Vukanovic-Stjecic et al., 2000), but there is evidence that the majority of T cells in COPD airways are of the Tc1 subtype (Saetta et al., 2002). CD8<sup>+</sup> and CD4<sup>+</sup> T cells show increased expression of activation markers compared with T cells in the circulation, although there is no clear difference between patients with COPD and normal controls (Leckie et al., 2003).

The mechanisms by which CD8<sup>+</sup> and, to a lesser extent, CD4<sup>+</sup> cells accumulate in the airways and lungs of patients with COPD are not yet understood. However, homing of T cells to the lung must depend on some initial activation followed by adhesion and selective chemotaxis. T cells in peripheral airways of COPD patients show increased expression of CXCR3, and there is in-
creased secretion of CXCR3-activating chemokines in COPD airways (Saetta et al., 2002).

There is also an increase in the numbers of CD8+ cells in the circulation in COPD patients who do not smoke (de Jong et al., 1997; Kim et al., 2002) and an increase in Th1 type [interferon (IFN)-γ producing] CD4+ cells in COPD patients (Majori et al., 1999). This indicates that there may be chronic immune stimulation via antigens presented via the human leukocyte antigen class I pathway. Dendritic Cells may migrate from the airways to regional lymph nodes and stimulate proliferation of CD8+ and CD4+ T cells. CD8+ cells are typically increased in airway infections, and it is possible that the chronic colonization of the lower respiratory tract of COPD patients by bacterial and viral pathogens is responsible for this inflammatory response (Hill et al., 2000). It is also possible that protease-induced lung injury may uncover previously sequestered autoantigens or that cigarette smoke itself may damage airway epithelial cells and make them antigenic (Cosio et al., 2002).

The role of increased numbers of CD4+ cells in COPD, particularly in severe disease, is also unknown (Retamales et al., 2001); it is possible that they have immunological memory and play a role in perpetuating the inflammatory process in the absence of cigarette smoking. Natural killer (NK; CD56+) cells are the first line of defense against viral infections. Circulating NK cells are reduced in patients with COPD and have reduced phagocytic activity (Prieto et al., 2001), and similar findings are found in normal smokers (Zeidel et al., 2002), although no difference in NK cells was found in lung parenchyma of COPD patients (Majo et al., 2001). There is an increase in γδ T cells in alveoli of smokers, whether they have airway obstruction or not (Majo et al., 2001).

The role of T cells in the pathophysiology of COPD is not yet certain. CD8+ cells have the capacity to cause cytolyis and apoptosis of alveolar epithelial cells through release of perforins, granzyme-B, and TNF-α (Hashimoto et al., 2000). There is an association between CD8+ cells and apoptosis of alveolar cells in emphysema (Majo et al., 2001). In a mouse model of cigarette-induced emphysema, there is a predominance of T cells, which are directly related to the severity of emphysema (Takubo et al., 2002).

4. Eosinophils. The role of eosinophils in COPD is uncertain. There are some reports of increased numbers of inactive eosinophils in the airways and lavage of patients with stable COPD, whereas others have not found increased numbers in airway biopsies, BAL, or induced sputum (Turato et al., 2001). The presence of eosinophils in patients with COPD predicts a response to corticosteroids and may indicate coexisting asthma (Brightling et al., 2000; Papi et al., 2000). Increased numbers of eosinophils have been reported in bronchial biopsies and BAL fluid during acute exacerbations of chronic bronchitis (Saetta et al., 1994, 1996). Surprisingly, the levels of eosinophil basic proteins in induced sputum are as elevated in COPD as in asthma, despite the absence of eosinophils, suggesting that they may have degranulated and are no longer recognizable by microscopy (Keatings and Barnes, 1997). Perhaps this is due to the high levels of neutrophil elastase that have been shown to cause degranulation of eosinophils (Liu et al., 1999).

5. Dendritic Cells. Dendritic cells play a central role in the initiation of the innate and adaptive immune response (Banchereau et al., 2000). The airways and lungs contain a rich network of dendritic cells that are localized near the surface, so they are ideally located to signal the entry of foreign substances that are inhaled (Holt and Stumbles, 2000). Dendritic cells can activate a variety of other inflammatory and immune cells, including macrophages, neutrophils, and T and B lymphocytes (Huang et al., 2001). It therefore likely that the dendritic cell may play an important role in the pulmonary response to cigarette smoke and other inhaled noxious agents and may therefore be a key cellular element in COPD. The mechanism by which tobacco smoke activates the immune system is not yet understood, but a glycoprotein isolated from tobacco has powerful immunostimulatory actions (Francus et al., 1988). There is an increase in the number of dendritic cells in rat lungs exposed to cigarette smoke (Zeid and Muller, 1995) and in the airways and alveolar walls of smokers (Casolaro et al., 1988; Soler et al., 1989). Pulmonary histiocytosis is a disease caused by dendritic cell granulomata in the lung and is characterized by destruction of the lung parenchyma, which resembles emphysema (Tazi et al., 1999, 2000). The adult form of the disease occurs almost exclusively in smokers. In mice exposed to chronic cigarette smoke, there is an increase in dendritic cells in the airways and lung parenchyma (D’Hulst et al., 2002). The role of dendritic cells in recruiting other effector cells in COPD deserves further study.

6. Epithelial Cells. Airway and alveolar epithelial cells may be an important source of inflammatory mediators and proteases in COPD. Epithelial cells are activated by cigarette smoke to produce inflammatory mediators, including TNF-α, IL-1β, GM-CSF, and IL-8 (Mio et al., 1997; Hellermann et al., 2002; Floreani et al., 2003). Epithelial cells in small airways may be an important source of TGF-β, which then induces local fibrosis (Takizawa et al., 2001). Vascular-endothelial growth factor (VEGF) appears to be necessary to maintain alveolar cell survival, and blockade of VEGF receptors (VEGFR2) in rats induces apoptosis of alveolar cells and an emphysema-like pathology (Kasahara et al., 2000). Airway epithelial cells are also important in defense of the airways. Mucus produced from goblet cells traps bacteria and inhaled particulates (Adler and Li, 2001). Epithelial cells secrete defensins and other cationic peptides with antimicrobial effects and are part of the innate defense system but are also involved in tissue re-
pair processes (Aarbiou et al., 2002). They secrete antioxidants as well as antiproteases, such as secretory leukoprotease inhibitor (SLPI). Epithelial cells also transport IgA and are therefore involved in adaptive immunity (Pilet et al., 2001). It is possible that cigarette smoke and other noxious agents impair these innate and adaptive immune responses of the airway epithelium, thereby increasing susceptibility to infection.

The airway epithelium in chronic bronchitis and COPD often shows squamous metaplasia, which may result from increased proliferation of airway epithelial cells. Proliferation in basal airway epithelial cells, measured by proliferative cell nuclear antigen, is increased in some normal smokers but is markedly increased in patients with chronic bronchitis and correlates with the degree of squamous metaplasia (Demoly et al., 1994). The nature of the growth factors involved in epithelial cell proliferation, cell cycle, and differentiation in COPD are not yet known. Epithelial growth factor receptors show increased expression in airway epithelial cells of smokers and may contribute to basal cell proliferation, resulting in squamous metaplasia and an increased risk of bronchial carcinoma (Franklin et al., 2002).

### III. Lipid Mediators

As in asthma, lipid mediators derived from arachidonic acid may play an important role in the pathophysiology of COPD.

#### A. Prostaglandins

1. **Prostaglandin E\(_2\).** There is an increase in the concentration of prostaglandin (PG)E\(_2\) in exhaled breath of COPD patients (Montuschi et al., 2003) (Fig. 7). This is likely to be derived from cyclooxygenase-2 (COX-2), which is expressed in alveolar macrophages (Jiang et al., 2003). There is increased COX-2 expression in alveolar macrophages from patients with COPD compared with normal control subjects (Taha et al., 2000). This is presumably a result of induction by inflammatory cytokines such as TNF-\(\alpha\) and IL-1\(\beta\), which activate NF-\(\kappa\)B, the key regulator of COX-2 (Newton et al., 1997). Inflammatory cytokines may also activate sphingomyelinase in the cell membrane to generate ceramide, which may also up-regulate COX-2 independently of NF-\(\kappa\)B (Newton et al., 2000).

PGE\(_2\) is a bronchodilator of human airways (Pavord and Tattersfield, 1995) and inhibits the release of proinflammatory cytokines from monocytes (Meja et al., 1997) and acetylcholine release from airway cholinergic nerves (via prostaglandin E\(_3\) receptors) (Spicuzza et al., 1998), suggesting that it may have beneficial effects in COPD airways. Furthermore, PGE\(_2\) markedly enhances the anti-inflammatory actions of phosphodiesterase-4 inhibitors, which are in clinical development as anti-inflammatory therapy for COPD (Au et al., 1998). However, PGE\(_2\) also has potentially detrimental effects in stimulating mucus secretion and expression of mucin genes (MUC5AC, MUCB) (Borchers et al., 1999) and in sensitizing and activating airway sensory nerves to enhance coughing (Stone et al., 1992; Lee et al., 2002). Inhalation of the nonselective COX inhibitor indomethacin is reported to reduce mucus hypersecretion in patients with COPD (Tamaoki et al., 1992), but long-term trials of COX inhibitors (and in particular COX-2 inhibitors) have not yet been undertaken.

2. **Prostaglandin F\(_{2\alpha}\).** PGF\(_{2\alpha}\) is also increased in exhaled breath condensate of COPD patients (Montuschi et al., 2003). PGF\(_{2\alpha}\) is a bronchoconstrictor and also activates airway sensory nerves to produce cough (Nichol et al., 1990).

3. **Thromboxane.** Thromboxane (Tx) B\(_2\) concentrations are not increased in exhaled breath of patients with COPD (Montuschi et al., 2003). However, the concentration of the major metabolite of thromboxane 11-dehydro-TxB\(_2\) is increased in the urine of patients with COPD, and this is correlated with the degree of hypoxia and reversed by supplementary oxygen therapy (Davi et al., 1997). The elevated concentrations of 11-dehydro-TxB\(_2\) are almost normalized by low doses of aspirin, indicating that they are likely to be derived from platelets. Thromboxane is a potent pulmonary vasoconstrictor and may contribute to the pulmonary hypertension in hypoxic COPD patients. A thromboxane receptor antagonist seratrodast reduces urinary 11-dehydro-TxB\(_2\) in COPD patients and is reported to reduce symptoms of dyspnea, but it has no effect on airway function (Horiguuchi et al., 2002).

#### B. Leukotrienes

1. **Leukotriene B\(_4\).** Human alveolar macrophages express cytosolic phospholipase A\(_2\) and release LTB\(_4\) and platelet-activating factor on activation (Shamsuddin et al., 1997). LTB\(_4\) is increased in exhaled breath condensate of patients with stable COPD (Montuschi et al., 2003) (Fig. 7) and is further increased during exacerbations (Biernacki et al., 2003). LTB\(_4\) is also increased in

![Fig. 7. Increased concentrations of LTB\(_4\) and PGE\(_2\) but not the cysteinyl-leukotriene LTE\(_4\) in exhaled breath condensate of patients with COPD. (Adapted from Montuschi et al., 2003).](image-url)
the sputum of patients with COPD, particularly during exacerbations (Hill et al., 1999; Woolhouse et al., 2002; Beeh et al., 2003c). Plasma concentrations of LTB₄ are also reported to be increased in COPD patients (Seggev et al., 1991). The cellular source of LTB₄ in COPD is likely to be from alveolar macrophages and neutrophils.

LTB₄ is a potent chemoattractant of neutrophils through the activation of BLT₁ receptors that are expressed predominantly on neutrophils. BLT₂ receptors are expressed on T lymphocytes (Yokomizo et al., 2000). BLT₁ antagonists, such as LY29311 (2-[2-propyl-3-[3-[2-ethyl-4-(4-fluorophenyl)-5-hydroxphenoxy]propoxy]phenoxy]benzoic acid), have now been developed for the treatment of neutrophilic inflammation (Silbaugh et al., 2000). BLT₁-receptor antagonists inhibit the neutrophil chemotactic activity of sputum from COPD patients, indicating the potential clinical value of such drugs (Crooks et al., 2000; Beeh et al., 2003c), but they only give about 25% inhibition, indicating that other neutrophil chemotactic factors are also involved. LTB₄ antagonists have also been shown to reverse lipopolysaccharide-induced survival of neutrophils from COPD patients (Lee et al., 2000).

2. Cysteinyl-leukotrienes. Cysteinyl-leukotrienes are increased in asthma and largely derived from mast cells, but there is no evidence that they are increased in COPD. Thus, exhaled breath condensate shows an increase in concentration of cysteinyl-LTs in adults and children with asthma, but not in patients with COPD (Csoma et al., 2002; Montuschi and Barnes, 2002b; Montuschi et al., 2003). There is no scientific rationale for the use of cysteinyl-leukotriene receptor antagonists, such as montelukast, in the treatment of COPD. However, it has recently been reported that montelukast improves some of the symptoms of COPD, although there is no improvement in objective lung function measurements (Rubinstein et al., 2004). This might indicate an effect on some other aspects of COPD, such as mucus secretion.

C. Platelet-Activating Factor

Platelet-activating factor (PAF) is a potent chemoattractant and activator of neutrophils. PAF is also produced by and activates alveolar macrophages (Shindo et al., 1998). There are no reports of PAF production in COPD patients, and there are no studies of PAF antagonists, so the role of PAF in COPD remains unknown.

IV. Reactive Oxygen Species

Oxidative stress is an important feature of COPD and there is increasing evidence that it is involved in its pathophysiology (Fig. 8). Oxidative stress occurs when reactive oxygen species (ROS) are produced in excess of the antioxidant defense mechanisms and result in harmful effects, including damage to lipids, proteins, and DNA. There is increasing evidence that oxidative stress is an important feature in COPD (Repine et al., 1997; Henricks and Nijkamp, 2001; MacNee, 2001).

A. Formation

Inflammatory and structural cells that are activated in the airways of patients with COPD produce ROS, including neutrophils, eosinophils, macrophages, and epithelial cells (MacNee, 2001). Superoxide anions (O₂⁻) are generated by NADPH oxidase, and this is converted to hydrogen peroxide (H₂O₂) by superoxide dismutases. H₂O₂ is then dismuted to water by catalase. O₂⁻ and H₂O₂ may interact in the presence of free iron to form the highly reactive hydroxyl radical (·OH). O₂⁻ and H₂O₂ may interact in the presence of free iron to form the highly reactive hydroxyl radical (·OH). O₂⁻ and H₂O₂ may interact in the presence of free iron to form the highly reactive hydroxyl radical (·OH). O₂⁻ and H₂O₂ may interact in the presence of free iron to form the highly reactive hydroxyl radical (·OH).
may also combine with NO to form peroxynitrite, which also generates ·OH (Beckman and Koppenol, 1996). Oxidative stress leads to the oxidation of arachidonic acid and the formation of a new series of prostanoid mediators called isoprostanes, which may exert significant functional effects (Morrow, 2000), including bronchoconstriction and plasma exudation (Kawikova et al., 1996; Okazawa et al., 1997; Janssen, 2001).

Granulocyte peroxidases, such as myeloperoxidase in neutrophils, play an important role in the generation of oxidative stress. In neutrophils, \( \text{H}_2\text{O}_2 \) generated from \( \text{O}_2^- \) is metabolized by myeloperoxidase in the presence of chloride ions to hypochlorous acid, which is a strong oxidant. Myeloperoxidase is also able to nitrate tyrosine residues, as can peroxynitrite (Eiserich et al., 1996; van der Vliet et al., 1999a; Gaut et al., 2002).

The lung is also exposed to exogenous oxidants, which presumably summate with endogenous ROS production to further enhance oxidative stress in the lungs. Cigarette smoke itself is a potent source of oxidants, and the gas phase has been estimated to contain over \( 10^{15} \) free radicals (Pryor and Stone, 1993). Some forms of air pollution, including ozone, nitrogen dioxide, and diesel particulates, are also an oxidative stress and are associated with increased prevalence and increased numbers of exacerbations of COPD (Sunyer, 2001).

B. Antioxidants

The normal production of oxidants is counteracted by several endogenous antioxidant mechanisms in the human respiratory tract (Cantin et al., 1990). Antioxidants may be enzymatic or nonenzymatic. The major enzymatic antioxidants in the airways are catalase, superoxide dismutase (SOD), glutathione peroxidase, glutathione S-transferase, xanthine oxidase, and thioredoxin. The nonenzymatic category of antioxidant defenses includes low molecular weight compounds such as glutathione, ascorbate, urate, \( \alpha \)-tocopherol, bilirubin, and lipoic acid. Concentrations of these antioxidants vary, depending on both subcellular and anatomic location. For example, glutathione is 100-fold more concentrated in the airway epithelial lining fluid compared with plasma (van der Vliet et al., 1999b). Oxidant stress activates the inducible enzyme heme oxygenase-1, converting heme and hemin to biliverdin with the formation of carbon monoxide (Choi and Alam, 1996). Biliverdin is converted via bilirubin reductase to bilirubin, which is a potential antioxidant. Heme oxygenase-1 is widely expressed in human airways (Lim et al., 2000a), and carbon monoxide production is increased in COPD (Montuschi et al., 2001). In the lung, intracellular antioxidants are expressed at relatively low levels and are not induced by oxidative stress, whereas the major antioxidants are extracellular (Comhair and Erzurum, 2002). Extracellular antioxidants, particularly glutathione peroxidase, are markedly up-regulated in response to cigarette smoke and oxidative stress. The glutathione system is the major antioxidant mechanism in the airways. There is a high concentration of reduced glutathione in lung epithelial lining fluid (Cantin et al., 1990), and concentrations are higher in cigarette smokers. Extracellular glutathione peroxidase is an important antioxidant in the lungs and may be secreted by epithelial cells and macrophages, particularly in response to cigarette smoke or oxidative stress (Avissar et al., 1996). Extracellular glutathione peroxidase inactivates \( \text{H}_2\text{O}_2 \) and \( \text{O}_2^- \) but also reactive nitrogen species (Comhair and Erzurum, 2002). Extracellular antioxidants also include the dietary antioxidants vitamin C (ascorbic acid) and vitamin E (\( \alpha \)-tocopherol), uric acid, lactoferrin, and extracellular SOD3. SOD3 is highly expressed in human lung, but its role in COPD is not yet clear (Bowler and Crapo, 2002).

C. Evidence for Increased Oxidative Stress

There is considerable evidence for increased oxidative stress in COPD (Repine et al., 1997; MacNee, 2001). As discussed above, oxidant stress is derived from cigarette smoke and from inflammatory cells, such as activated macrophages and neutrophils. Epidemiological evidence indicates that reduced dietary intake of antioxidants may be a determinant of COPD, and population surveys have linked a low dietary intake of the antioxidant ascorbic acid with declining lung function (Britton et al., 1995; Schunemann et al., 2001).

1. Pulmonary Oxidative Stress. There is abundant evidence for increased oxidative stress in the lungs of patients with COPD. Using electromagnetic spin trapping, a marked increase in xanthine/xanthine oxidase activity has been detected in BAL fluid of COPD patients (Pinamonti et al., 1998). A specific marker lipid peroxidation, 4-hydroxy-2-nonenal, which forms adducts with basic amino acid residues in proteins, can be detected by immunocytochemistry and has been detected in lungs of patients with COPD (Rahman et al., 2002). This signature of oxidative stress is localized to airway and alveolar epithelial cells, endothelial cells, and neutrophils.

2. Exhaled Markers of Oxidative Stress. There are several markers of oxidative stress that may be detected in the breath, and several studies have demonstrated increased production of oxidants in exhaled air or breath condensates (Khartonov and Barnes, 2001; Montuschi and Barnes, 2002a; Paredi et al., 2002). Ethane, a volatile hydrocarbon formed through lipid peroxidation, is increased in the breath of COPD patients, and the concentration correlates with disease severity (Paredi et al., 2000). There is an increased concentration of \( \text{H}_2\text{O}_2 \) in exhaled breath condensate of patients with COPD, particularly during exacerbations (Dekhuijzen et al., 1996; Nowak et al., 1999). There is also an increase in the concentration of 8-isoprostaglandin \( \text{F}_{2\alpha} \) (8-isoprostane) in exhaled breath condensate, which is found even in
patients who are ex-smokers (Montuschi et al., 2000) and is increased further during acute exacerbations (Biernacki et al., 2003). 8-Isoprostan e is also increased in the breath of normal smokers, but to a lesser extent than in COPD, suggesting that there is an exaggeration of oxidative stress in COPD. Malondialdehyde and thiobarbituric acid reactive substances, which are markers of lipid peroxidation, are also increased in exhaled breath condensate of patients with COPD (Nowak et al., 1999; Corradi et al., 2003).

3. Systemic Markers of Oxidative Stress. There is also evidence for increased systemic markers of oxidative stress in patients with COPD as measured by biochemical markers of lipid peroxidation (Rahman et al., 1996). Increased plasma concentrations of malondialdehyde have been reported in COPD patients (Calikoglu et al., 2002). 8-Isoprostan e is increased in the urine of patients with COPD and further increased during exacerbations (Pratico et al., 1998). The interaction of O$_2^-$ and NO forms peroxynitrite, which forms stable 3-nitrotyrosine adducts, as a footprint of oxidative stress, as discussed below.

D. Effects on Airway Function

ROS have several effects on the airways, which would have the effect of increasing the inflammatory and destructive response in COPD. These effects may be mediated by direct actions of ROS on target cells in the airways but may also be mediated indirectly via activation of signal transduction pathways and transcription factors and via the formation of oxidized mediators, such as isoprostanes and hydroxyl-nonenal.

1. Effects on Transcription Factors. ROS activate NF-kB, which switches on multiple inflammatory genes resulting in amplification of the inflammatory response (Barnes and Karin, 1997). The molecular pathways by which oxidative stress activates NF-kB have not been fully elucidated, but there are several redox-sensitive steps in the activation pathway (Janssen-Heininger et al., 2000). Many of the stimuli that activate NF-kB appear to do so via the formation of ROS, particularly H$_2$O$_2$. ROS activate NF-kB in an epithelial cell line (Adcock et al., 1994) and increase the release of proinflammatory cytokines from cultured human airway epithelial cells (Rusznak et al., 1996). Oxidative stress results in activation of histone acetyltransferase activity, which opens up the chromatin structure and is associated with increased transcription of multiple inflammatory genes (Rahman, 2003; Tomita et al., 2003).

Another transcription factor that activates inflammatory genes is activator protein-1, a heterodimer of Fos and Jun proteins. As with NF-kB, there are several redox-sensitive steps in the activation pathway (Xanthoudakis and Curran, 1996).

2. Effects on Signal Transduction Pathways. Oxidants also activate mitogen-activated protein (MAP) kinase pathways. H$_2$O$_2$ is a potent activator of extracellular regulated kinases (ERK) and p38 MAP kinase pathways that regulate the expression of many inflammatory genes and survival in certain cells and spreading of macrophages (Ogura and Kitamura, 1998). Indeed, many aspects of macrophage function are regulated by oxidants through the activation of multiple kinase pathways (Forman and Torres, 2002).

3. Effects on Target Cells. H$_2$O$_2$ directly constricts airway smooth muscle in vitro (Rhoden and Barnes, 1989), and hydroxyl radicals (OH$^-$) potently induce plasma exudation in airways (Lei et al., 1996). 8-Isoprostan e (or 8-epi-prostaglandin F$_{2\alpha}$), the predominant isoprostan e formed by the nonenzymatic oxidation of arachidonic acid in humans, is a potent constrictor of animal and human airways in vitro, an effect that is largely mediated via thromboxane receptors (Kawikova et al., 1996). In rat airways, oxidant stress increases cholinergic nerve-induced bronchoconstriction, an effect that may be due to oxidant damage of acetylcholinesterase (Ohru et al., 1991). 8-Isoprostan e also has direct effects on airway nerves (Spicuzza et al., 2001).

Little is known about the effects of ROS on the vasculature. OH$^-$ potently induces plasma exudation in rodent airways (Lei et al., 1996), and 8-isoprostan e is a potent inducer of plasma exudation in airways (Okazawa et al., 1997), but their effects on pulmonary vessels are not known.

In rats, oxidative stress increases airway mucus secretion, an effect that is blocked by cyclo-oxygenase inhibitors (Adler et al., 1990). The effect of oxidative stress may be mediated via the activation of epidermal growth factor receptors (EGFR) on submucosal glands (Takeyama et al., 2000). Neutrophil elastase is a potent stimulant of mucus secretion and increases the expression of mucin genes (MUC5AC); its effects are inhibited by dimethylthiourea, a purported scavenger of OH$^-$ (Fischer and Voynow, 2000). Oxidative stress may induce proliferation of airway epithelial cells, and this effect also appears to be mediated via activation of EGFR (Tamaoiki et al., 2004).

4. Effects on Inflammatory Response. The increased oxidative stress in the airways of COPD patients may play an important pathophysiological role in the disease by amplifying the inflammatory response in COPD. This may reflect the activation of NF-kB and activator protein-1, which then induce a neutrophilic inflammation via increased expression of IL-8 and other CXC chemokines, TNF-$\alpha$ and MMP-9. Oxidative stress may therefore serve to amplify the ongoing chronic inflammatory response in COPD and may be an important mechanism leading to increased inflammation during acute exacerbations.

5. Effect on Proteases. Oxidative stress may also impair the function of antiproteases such as $\alpha_1$-antitrypsin and SLPI and thereby accelerates the breakdown of elastin in lung parenchyma (Taggart et al., 2000).
6. Effect on Steroid Responsiveness. Corticosteroids are much less effective in COPD than in asthma and do not reduce the progression of the disease (Pauwels et al., 1999; Vestbo et al., 1999; Burge et al., 2000; Lung Health Study Research Group, 2000). In contrast to patients with asthma, those with COPD do not show any significant anti-inflammatory response to corticosteroids (Keatings et al., 1997; Culpitt et al., 1999). Alveolar macrophages from patients with COPD show a marked reduction in responsiveness to the anti-inflammatory effects of corticosteroids, compared with cells from normal smokers and nonsmokers (Culpitt et al., 2003). Recent studies suggest that there may be a link between oxidative stress and the poor response to corticosteroids in COPD. Oxidative stress impairs binding of glucocorticoid receptors to DNA and the translocation of these receptors from the cytoplasm to the nucleus (Hutchison et al., 1991; Okamoto et al., 1999). Corticosteroids switch off inflammatory genes by recruiting HDAC2 to the active transcription site, and by deacetylating the hyperacetylated histones of the actively transcribing inflammatory gene, they are able to switch off its transcription and thus suppress inflammation (Ito et al., 2000; Barnes et al., 2003). In cigarette smokers and patients with COPD, there is a marked reduction in activity of HDAC and reduced expression of HDAC2 in alveolar macrophages (Ito et al., 2001a) and an even greater reduction in HDAC2 expression in peripheral lung tissue (Ito et al., 2001b). This reduction in HDAC activity is correlated with reduced expression of inflammatory cytokines and a reduced response to corticosteroids. This may result directly or indirectly from oxidative stress and is mimicked by the effects of H$_2$O$_2$ in cell lines (Ito et al., 2001b).

7. Effects on Apoptosis. Oxidative stress may also induce apoptosis in endothelial and epithelial cells (Haddad, 2004). Apoptosis of type 1 pneumocytes may be contributory to the development of emphysema, and this might be induced by cytotoxic T lymphocytes or by inhibition of vascular-endothelial growth factor receptors (Kasahara et al., 2000; Majo et al., 2001). ROS may induce apoptosis by activating the NF-$\kappa$B pathway, by direct DNA damage via activation of poly-ADP-ribose, and via the generation of 4-hydroxy-2$n$onenal. Apoptosis signal-regulating kinase-1 is held in an inactive conformation by thioredoxin, and when oxidized by ROS, this triggers apoptotic pathways (Gotoh and Cooper, 1998).

8. Systemic Effects. The systemic oxidative stress in COPD may contribute to the systemic effects seen in severe disease. For example, impaired redox balance in skeletal muscle cells may be contributory to the muscle weakness, fatigability, and wasting seen in some patients (Langen et al., 2003).

E. Effects of Antioxidants

In view of the persuasive evidence presented above that oxidative stress is important in the pathophysiology of COPD, antioxidants are a logical approach to therapy (MacNee, 2000; Barnes, 2001c).

Several antioxidants have also been administered to patients with COPD to explore their effects on lung function. N-Acetyl cysteine was developed as a mucolytic agent but also acts as an antioxidant by increasing the formation of glutathione. Although small-scale trials failed to demonstrate any clear clinical benefit, more recent meta-analyses have shown a small but significant clinical benefit in COPD, particularly in reducing exacerbations (Grandjean et al., 2000; Poole and Black, 2001). This benefit is not shared by other mucolytics and is therefore likely to be due to the antioxidant effect of N-acetyl cysteine. These results should encourage the development of more effective antioxidants in the future. Currently available antioxidants are rather weak, but more potent drugs, including spin-trap antioxidants (nitrones) and stable glutathione analogs, are currently in clinical development (Cuzzocrea et al., 2001).

V. Nitric Oxide

A. Formation

1. Nitric Oxide. NO is generated in COPD from the enzyme inducible NO synthase (iNOS), which is expressed in macrophages and lung parenchyma of patients with COPD, particularly in patients with severe disease (Ichinose et al., 2000; Maestrelli et al., 2003). NO is markedly increased in exhaled breath of patients with mild asthma, reflecting the inflammatory process in the airways, but in patients with COPD exhaled NO levels are little raised above normal (Maziak et al., 1998; Corradi et al., 1999; Rutgers et al., 1999) but are more clearly increased during exacerbations (Maziak et al., 1998; Agusti et al., 1999).

2. Peroxynitrite. The reason why exhaled NO may be elevated in COPD as much as in asthma may be because exhaled NO levels are depressed by cigarette smoking and oxidative stress, since NO combines avidly with superoxide anions to form peroxynitrite. This is supported by the fact that nitrate concentrations, formed by metabolism of peroxynitrite, are increased in breath condensate and sputum of cigarette smokers and patients with COPD (Corradi et al., 2001; Kanazawa et al., 2003c). Generation of superoxide anions from neutrophils also decreases the amount of NO formed by an epithelial cell line in vitro, as NO is consumed to form peroxynitrite (Jones et al., 1998). There is also a reduction in the undefined “peroxynitrite inhibitory activity” in sputum of COPD patients (Kanazawa et al., 2003c). Peroxynitrite reacts with tyrosine residues in certain proteins to form 3-nitrotyrosine, which may be detected immunologically. There is increased 3-nitrotyrosine immunoreactivity in sputum macrophages from patients with COPD (Ichinose et al., 2000). There is also an increase in the tyrosine nitration of proteins in sputum of COPD patients compared with normal controls, and
this is correlated with disease severity (Sugiura et al., 2004).

Oxidative stress and peroxynitrite may also reduce HDAC2 levels, thereby inducing resistance to the anti-inflammatory actions of corticosteroids (Barnes et al., 2004). This may be the result of nitration of critical tyrosine residues in the structure of HDAC2, which impairs its enzymatic activity (Ito et al., 2004). Peroxynitrite appears to induce steroid resistance in vitro through this molecular mechanism. Nitration of other regulatory proteins may also be an important mechanism of disease in COPD that has not yet been explored. Peroxynitrite infusion causes a neutrophilic inflammatory response in rabbit lungs (Farshid et al., 2002). It may also induce cell damage. Peroxynitrite activates MAP kinase pathways in airway epithelial cells and may induce apoptosis of epithelial cells, particularly through the activation of the ERK pathway (Nabeyrat et al., 2003). Peroxynitrite is a potent pulmonary vasoconstrictor in an isolated perfused rat lung preparation, but it does not affect hypoxic vasoconstrictor responses (Nossumo et al., 2004).

B. Inhibition

Inhibitors of iNOS may inhibit formation of peroxynitrite and may be of value in therapy of the potential detrimental role of peroxynitrite. Selective, potent, and long-lasting inhibitors of iNOS are now in clinical development (Hansel et al., 2003). The selenium-containing antioxidant ebselen is reported to be effective as an efficient scavenger of peroxynitrite (Sies and Masumoto, 1997) but does not appear to be in clinical development.

VI. Peptide Mediators

A. Endothelins

1. Formation. There is an increased concentration of endothelin-1 (ET-1) in induced sputum and bronchoalveolar lavage fluid of patients with COPD (Chalmers et al., 1999; Bacakoglu et al., 2003), particularly during exacerbations (Roland et al., 2001). Plasma ET-1 concentrations are also elevated in COPD patients, particularly in patients who develop nocturnal hypoxemia during the night (Trakada et al., 2001; Spiropoulos et al., 2003) and in patients with hypoxemia (Faller et al., 1998), but it is not correlated with secondary pulmonary hypertension (Bacakoglu et al., 2003). This may reflect the release of ET-1 by hypoxemia, suggesting that the release of ET-1 may contribute to pulmonary vasoconstriction and pulmonary hypertension in COPD patients.

2. Effects. ET-1 is a potent vasoconstrictor and also causes vascular smooth muscle hyperplasia. There is increased expression of ET-1 in pulmonary endothelial cells of patients with COPD who have secondary pulmonary hypertension (Giaid et al., 1993), suggesting that ET-1 may contribute to the vascular remodeling associated with hypoxic pulmonary hypertension.

3. Therapeutic Potential. There is increasing evidence that endothelin antagonists (ET\textsubscript{A}-receptor antagonists) reduce pulmonary hypertension in pulmonary hypertension (Kenyon and Nappi, 2003). Several endothelin antagonists are in clinical development, and the nonselective ET-receptor antagonist bosentan is now used in the therapy of primary pulmonary hypertension. It is not yet certain whether it is clinically useful in the secondary pulmonary hypertension that occurs in severe COPD.

B. Bradykinin

Although the roles of bradykinin and related kinins in asthma have been extensively explored (Barnes, 1992), there is very little information about kinins in COPD. It is likely that kinins are generated in the airways of COPD patients as plasma exudation occurs. Furthermore, proinflammatory cytokines that are found in COPD airways increase the expression of bradykinin B\textsubscript{1}- and B\textsubscript{2}-receptors in pulmonary cells (Tsukagoshi et al., 1995; Trevisani et al., 1999; Haddad et al., 2000). Bradykinin is a potent bronchoconstrictor of human airways, particularly small airways (Hulsmann et al., 1994), stimulates mucus secretion (Nagaki et al., 1996), and potently potentiates cough by an effect on unmyelinated sensory nerve endings in the airways (Fox et al., 1996).

C. Tachykinins

1. Formation. Increased substance P concentrations have been reported in induced sputum of patients with chronic bronchitis (Tomaki et al., 1995); this is presumably derived from sensory nerve endings, although nonneuronal sources of tachykinins are now recognized. For example, rat alveolar macrophages express preprotachykinin-1 and synthesis substance P in response to endotoxin stimulation (Killingsworth et al., 1997), and human sputum macrophages express substance P in response to endotoxin (Germonpre et al., 1999). Tachykinin receptors are expressed in the human respiratory tract with NK\textsubscript{1}- and NK\textsubscript{2}-receptors localized to submucosal glands, blood vessels, and airway smooth muscle, whereas NK\textsubscript{2}-receptors are also expressed on inflammatory cells, including macrophages and T lymphocytes (Mapp et al., 2000). There is no difference in the distribution of receptors between normal subjects and smokers with or without airway obstruction.

Tachykinins are metabolized by neutral endopeptidase 24.11, which is strongly expressed in airway epithelial cells (Nadel, 1990). Although a reduction in neutral endopeptidase activity and expression has been implicated in worsening of asthma, there have been no studies of the role of this enzyme in COPD.

2. Effects. Tachykinins are potent stimulants of submucosal gland and goblet cell secretion. The effects of
cigarette smoke on mucus secretion is also blocked by tachykinin antagonists in experimental animals, indicating that tachykinin release from sensory nerves mediates these effects (Tokuyama et al., 1990). Substance P stimulates secretion from human airways in vitro, and this effect is mediated via NK1-receptors (Rogers et al., 1989). In porcine airways, tachykinins elicit submucosal gland section via NK1-receptors in gland cells, but also via NK2-receptors on cholinergic nerve terminal (Philips et al., 2003). Neurokinin-A activates alveolar macrophages of smokers via NK2-receptors (Brunelleschi et al., 1996), suggesting that tachykinins have the potential to enhance inflammation in COPD airways.

3. Therapeutic Potential. Tachykinin antagonists have therapeutic potential in COPD, particularly for reducing neurogenic mucus secretion stimulated by cigarette smoke exposure (Joos and Pauwels, 2001; Barnes, 2002a). There are no reported studies of tachykinin receptor antagonists in COPD patients.

D. Complement Fragments

Activation of complement generates several complement fragments that have potent chemotactic activity. C5a (anaphylatoxin) is derived from cleavage of complement protein C5 when the classical complement cascade is activated. Once formed, C5a can bind immediately to neutrophils in the circulation and acts as a potent chemotactic agent (Ward, 2004). C5 is also produced by tissue macrophages and type II pneumocytes in the lung as a component of the alternative complement cascade (Strunk et al., 1988). The two pathways promote an inflammatory gradient enhancing subsequent migration. C5a enhances adhesion molecule expression (especially intercellular adhesion molecule-1) in airway epithelial cells, and this effect was exaggerated in the presence of cigarette smoke (Floreaani et al., 2003). Sputum concentrations of C5a, but not C3a or C4a, are elevated in COPD patients (Marc et al., 2004), suggesting that this may contribute to the neutrophil chemotactic activity of sputum in COPD patients.

VII. Chemokines

Over 50 different chemokines are now recognized, and they activate up to 20 different surface receptors (Rossi and Zlotnik, 2000). Chemokine receptors belong to the 7 transmembrane receptor superfamily of G-protein-coupled receptors, and this makes it possible to discover small molecule inhibitors, which has not been possible for classical cytokine receptors (Proudfoot, 2002). Some chemokines appear to be selective for single chemokine receptors, whereas others are promiscuous and mediate the effects of several related chemokines. Four different families of chemokines are now differentiated, based on differences in the position of critical cysteine residues; CC, CXC, Cm, and CX3C chemokines are recognized. Each chemokine molecule binds to a single or several receptors expressed on target inflammatory cells, resulting in the activation of signal transduction pathways that then result in chemotaxis or other cellular activities that include proliferation, differentiation, and survival. Chemokines appear to act in sequence in determining the final inflammatory response, so inhibitors may be more or less effective depending on the kinetics of the response (Gutierrez-Ramos et al., 2000).

Chemokines play a critical role in orchestrating inflammatory and immune responses by regulating the trafficking of inflammatory and immune cells to target organs (Olson and Ley, 2002). Several chemokines are involved in the recruitment of inflammatory cells in COPD (Lukacs, 2001). There is considerable interest in identifying chemokines in COPD as small molecule chemokine receptor inhibitors are now in development for COPD (Barnes, 2002b; Panina-Bordignon and D’Ambrosio, 2003).

A. Interleukin-8

1. Formation. The CXC chemokine IL-8 (CXCL8) is a potent chemotactant of neutrophils, and it is not surprising that it has been implicated in COPD.

IL-8 levels are markedly increased in induced sputum of patients with COPD and correlate with the increased proportion of neutrophils (Keatings et al., 1996; Yamamoto et al., 1997). The concentrations of IL-8 are even more elevated in patients with emphysema due to α1-antitrypsin deficiency (Woolhouse et al., 2002). The concentrations of IL-8 in induced sputum are further increased during acute exacerbations, which presumably contributes to the increased numbers of neutrophils and the increased purulence of the sputum (Crooks et al., 2000; Aaron et al., 2001; Gompertz et al., 2001). There is a correlation between IL-8 concentrations and the bacterial colony count in sputum, indicating that bacterial infection may induce neutrophilic inflammation, at least in part, via induction of IL-8 release in the airways (Hill et al., 2000; Patel et al., 2002). IL-8 is also increased in BAL fluid of patients with COPD and correlates with numbers of neutrophils (Nocker et al., 1996; Soler et al., 1999). The concentrations of IL-8 are significantly higher in smokers with emphysema than in matched smokers without airflow limitation, whereas the concentrations of other CXC chemokines in BAL do not appear to discriminate between these groups (Tanino et al., 2002). IL-8 concentrations are also increased in hospitalized COPD patients and are correlated with skeletal muscle weakness (Spruit et al., 2003).

IL-8 is not stored and is synthesized in several cell types, predominantly epithelial cells, macrophages, and neutrophils, on cell stimulation with various agents (Mukaida, 2003). The cellular source of IL-8 in COPD is not completely certain. Airway epithelial cells secrete IL-8 in response to several stimuli, including TNF-α, IL-1β, bacterial products, lipopolysaccharides (LPS), certain viruses, oxidative stress, and cigarette smoke.
NF-κB activity is often regulated at the transcriptional level by several transcription factors, among which NF-κB is predominant. MMP-9 appears to increase the activity of IL-8 by up to 10-fold by truncating the amino terminal (Van Den Steen et al., 2000). Release of IL-8 is regulated mainly by neutrophils and is inhibited through inhibition of the NF-κB activity of sputum from patients with COPD (Crooks et al., 2000). Neutralization of IL-8 with a blocking antibody significantly reduces the neutrophil chemotactic activity of sputum from patients with COPD (Nakamura et al., 1991a,b; DeForge et al., 1993; Kwon et al., 1994; Johnston et al., 1998; Schulz et al., 2004). Interestingly, cultured airway epithelial cells and alveolar macrophages from COPD patients produce more IL-8 than cells from normal smokers, indicating an amplified response (Culpitt et al., 2003; Schulz et al., 2004). IL-8 protein and mRNA are increased in bronchiolar epithelial cells of patients with COPD (de Boer et al., 2000), and there is increased basal release of IL-8 from airway epithelial cells of patients with COPD (Profita et al., 2003; Schulz et al., 2003). Alveolar macrophages also secrete IL-8 in response to the same stimuli, and cells derived from patients with COPD secrete more IL-8 than those from normal smokers, who in turn secrete more macrophages than do normal nonsmokers (Culpitt et al., 2003). Neutrophils themselves also release IL-8 and attract more neutrophils; therefore, a self-perpetuating inflammatory state may be established (Bazzoni et al., 1991). The secretion of IL-8 is regulated transcriptionally by several transcription factors, among which NF-κB is predominant (Fig. 9). MMP-9 appears to increase the activity of IL-8 by up to 10-fold by truncating the amino terminal (Van Den Steen et al., 2000). Release of IL-8 is regulated mainly by increased transcription in response to the transcription factor NF-κB (Carter et al., 1998; DiMango et al., 1998) and is inhibited through inhibition of the NF-κB activating kinase IKK2 (inhibitor of NF-κB kinase-2) (Jazrawi et al., 2003). The activation of NF-κB results in histone hyperacetylation, which results in local unwinding of DNA and increased transcription of the IL-8 gene (Tobita et al., 2003). IL-8 secretion also appears to be regulated through p38 MAP kinase and ERK pathways (Wang et al., 2003).

2. Effects. Neutralization of IL-8 with a blocking antibody significantly reduces the neutrophil chemotactic activity of sputum from patients with COPD (Crooks et al., 2000; Beeh et al., 2003c). The reduction in neutrophil chemotactic activity is only of the order of approximately 30%, however, indicating that other neutrophil chemotactic factors are also involved and that blocking IL-8 alone may be insufficient as a therapeutic strategy to reduce neutrophil inflammation in the respiratory tract.

IL-8 acts via two receptors: CXCR1, which is a low-affinity receptor that is specific for IL-8, and CXCR2, which has high affinity and is shared by other CXC chemokines (Fig. 10). It is likely that CXCR2 mediates the chemotactic response of neutrophils and monocytes to IL-8, whereas CXCR1 may mediate the effects of IL-8 on release of mediators and proteases. There is a marked up-regulation of CXCR2 in airway epithelial cells during acute exacerbations of COPD, and this is correlated with the increased numbers of neutrophils in the airway (Qiu et al., 2003).

Binding of IL-8 to CXCR1 and -2 activates protein kinase B (Akt) and GTPases, which lead to enhanced neutrophil adherence to endothelial cells (by increasing expression of β2-integrins) and directed cell migration. Protein kinase B activates phosphoinositide 3 kinase, which induces F-actin polymerization, resulting in pseudopod formation and chemotaxis (Chodniewicz and Zhelev, 2003). There is also activation of Ras and MAP kinases in neutrophils, causing degranulation. These effects can be down-regulated by intracellular regulator of G-protein signaling proteins, which decrease the half-life of the active GTP-bound state of CXCR, leading to reduced IL-8-induced neutrophil migration and adherence (Bowman et al., 1998).

3. Therapeutic Potential. As discussed above, anti-IL-8 antibodies reduce the neutrophil chemotactic activity of COPD sputum (Crooks et al., 2000; Beeh et al., 2003b), but this is a partial effect, making it unlikely that blocking IL-8 alone would have a major clinical impact in COPD. This is because other CXC chemokines and other neutrophil chemotactic mediators such as LTB4 and C5a are also involved. A monoclonal antibody to IL-8 has been developed (Yang et al., 1999) and has been tested in COPD without reported success. The chemotactic response of neutrophils and monocytes to IL-8 is mediated via CXCR2, and as other CXC chemokines implicated in COPD (see section VII.D.) also act through this receptor, antagonism of CXCR2 may be a more effective strategy. Several small molecule inhibitors of CXCR2 are now in clinical development for the treatment of COPD (White et al., 1998; Hay and Sarau, 2001). In CXCR2 knockout mice, there is a marked reduction in mucus secretion in response to viral infection, implicating this receptor in mucus hypersecretion (Miller et al., 2003).

B. Growth-Related Oncogene-α

Growth-related oncogene-α (GRO-α; CXCL1) is another CXC chemokine that is involved in COPD. GRO-α
is secreted by alveolar macrophages and airway epithelial cells in response to stimulation with TNF-α and IL-17 (Jones and Chan, 2002; Prause et al., 2003; Schulz et al., 2004). Epithelial cells from COPD patients produce greater amounts of GRO-α than cells from normal smokers (Schulz et al., 2004). GRO-α activates neutrophils, monocytes, basophils, and T lymphocytes via CXCR2 (Geiser et al., 1993) (Fig. 9). The concentrations of GRO-α were markedly elevated in induced sputum and BAL of patients with COPD compared with normal smokers and nonsmokers (Traves et al., 2002) (Fig. 11). GRO-α is released in greater amounts from BAL cells from smokers compared with nonsmokers (Morrison et al., 1998). GRO-α selectively activates CXCR2 and is chemotactic for neutrophils and monocytes. There is an increase in the monocyte chemotactic response to GRO-α in COPD patients, and this may be related to increased turnover of CXCR2 in monocytes from COPD patients (Traves et al., 2004). It is possible that the increased chemotactic response of monocytes to GRO-α is one of the mechanisms leading to increased numbers of alveolar macrophages in the lungs of patients with COPD (Retamales et al., 2001) and could be one of the molecular mechanisms of susceptibility to cigarette smoking.

C. Epithelial Cell-Derived Neutrophil-Activating Peptide-78

Epithelial cell-derived neutrophil-activating peptide-78 (ENA-78; CXCL5) is derived predominantly from epithelial cells and also activates CXCR2 (Imaizumi et al., 1997), although monocytes do not appear to show an increased chemotactic response to this chemokine as they do to GRO-α (Traves et al., 2004). ENA-78 is increased in BAL fluid of COPD patients compared with normal subjects, but there is no difference between patients with emphysema and normal smokers (Tanino et al., 2002). BAL cells from smokers release more ENA-78 than cells from nonsmokers (Morrison et al., 1998). A marked increase in expression of ENA-78 has been reported in epithelial cells during exacerbations of COPD (Qiu et al., 2003).
D. CXC Chemokines

The mechanisms by which CD8⁺ and, to a lesser extent, CD4⁺ cells accumulate in the airways and lungs of patients with COPD are not yet understood. However, homing of T cells to the lung depends on initial activation followed by adhesion and selective chemotaxis. T cells in peripheral airways of COPD patients show increased expression of CXCR3, a receptor activated by interferon-γ inducible protein of 10 kDa (IP-10; CXCL10), monokine induced by interferon-γ (Mig; CXCL9), and interferon-inducible T cell-α chemoattractant (I-TAC; CXCL11). All three chemokines activate CXCR3, although I-TAC has the highest affinity (Clark-Lewis et al., 2003). CXCR3 is expressed on T lymphocytes, particularly of the CD8⁺ subtype. There is increased expression of IP-10 by bronchiolar epithelial cells and airway smooth muscle cells, and this could therefore contribute to the accumulation of CD8⁺ cells, which preferentially express CXCR3 (Saetta et al., 2002; Panzner et al., 2003; Hardaker et al., 2004). It is of interest that interferon-γ stimulates dendritic cells to produce IP-10 and Mig, which then enhance their ability to attract CD8⁺ cells (Padovan et al., 2002). Alveolar macrophages also have the capacity to produce IP-10 and Mig and thus attract CD8⁺ T cells (Agostini et al., 2000). Since CD8⁺ Tc1 cells produce interferon-γ, this provides a potential feed-forward amplification loop. The role of CD8⁺ T cells in COPD is not yet certain, but because they have the capacity to produce perforins and granzyme B, they might induce apoptosis in alveolar epithelial and endothelial cells, thereby contributing to emphysema (Majo et al., 2001; Cosio et al., 2002) (Fig. 12).

E. Monocyte Chemoattractant Protein-1

1. Production in Chronic Obstructive Pulmonary Disease. Monocyte chemotactic protein-1 (MCP-1; CCL2) is a CC-chemokine that activates CCR2 on monocytes and T lymphocytes (Rose et al., 2003). CCR2 may play a role in COPD, as MCP-1 levels are increased in sputum, bronchoalveolar lavage, and lungs of patients with COPD (Fig. 11), and MCP-1 is expressed in alveolar macrophages, T lymphocytes, and epithelial cells (Capelli et al., 1999; de Boer et al., 2000; Travas et al., 2002). MCP-1 is also secreted basally by type II pneumocytes in culture, and release is stimulated by LPS but inhibited by cigarette smoke extract (Witherden et al., 2004). CCR2 are down-regulated via Toll-like receptors 2 and 4 and other inflammatory receptors, which may provide a mechanism for terminating the chemotactic response in the lungs, resulting in an accumulation of monocytes (Parker et al., 2004).

2. Effects in Chronic Obstructive Pulmonary Disease. MCP-1 is a potent chemoattractant of monocytes and may therefore be involved in the recruitment of macrophages in COPD. Indeed, the chemoattractant effect of induced sputum from patients with COPD is almost completely abrogated by an antibody to CCR2. Since macrophages appear to play a critical role in COPD as a source of elastases and neutrophil chemoattractants, blocking CCR2 may be a useful therapeutic strategy in COPD. Several small molecule inhibitors and blocking antibodies are in development (initially for the treatment of rheumatoid arthritis) (Mirzadegan et al., 2000).

F. Macrophage Inflammatory Protein

Macrophage inflammatory protein (MIP)-1α is released by macrophages and has chemotactic activity for monocytes and neutrophils via CCR1. However, concentrations are not apparently increased in BAL fluid of smokers with or without chronic bronchitis, whereas MIP-1β concentrations are increased in patients with chronic bronchitis but not in asymptomatic smokers (Capelli et al., 1999).

G. Eosinophil-Selective Chemokines

As discussed above, eosinophils are increased in COPD airways and lungs, although they are not the predominant inflammatory cells as they are in asthma. Several chemokines have chemoattractant effects on eosinophils; this is mediated via CCR3, which is expressed predominantly on eosinophils. In COPD there is a small increase in eosinophils and eosinophil basic proteins in induced sputum and bronchoalveolar lavage fluid, and an increase in eosinophils has been described in exacerbations of chronic bronchitis (Saetta et al., 1994; Keatings et al., 1996; Pesci et al., 1998). This suggests that eosinophil chemoattractants may play some role, particularly during exacerbations. RANTES (released by activated normal T cells expressed and secreted; CCL5) activates CCR3 and is strongly expressed in airway epithelial cells of patients with chronic bronchitis exacerbations (Zhu et al., 2001). Eotaxin (CCL11) and CCR3 show increased expression in the bronchi of patients with exacerbations of chronic bronchitis and are corre-
lated with increased numbers of eosinophils (Bocchino et al., 2002).

H. Lymphocyte-Selective Chemokines

CCR4, CCR8, and CXCR4 are selectively expressed on TH2 cells and are activated by the chemokines macrophage-derived chemokine (CCL22), thymus- and activation-dependent chemokine (TARC, CCL17), and stromal cell-derived factor 1α (CXCL12), respectively (Lloyd et al., 2000). However, TH2 cells are not prominent in COPD, so it is unlikely that these receptors are relevant.

I. Dendritic Cell-Selective Chemokines

CCR7 plays a role in the migration of dendritic cells to regional lymph nodes, and therefore blocking this receptor might suppress antigen presentation (Sallusto and Lanzavecchia, 2000). There is an increase in the number of dendritic cells in rat lungs exposed to cigarette smoke (Zeid and Muller, 1995; D’Hulst et al., 2002) and in the airways and alveolar walls of smokers (Casolaro et al., 1988; Soler et al., 1989), but the chemotactic factors involved have not yet been determined. MIP-3α (CCL20) acts on CCR6, which is expressed by immature dendritic cells, is a potent chemoattractant of dendritic cells and is expressed by airway epithelial cells in response to IFN-γ (Reibman et al., 2003).

J. CX3C Chemokines

The unique CX3C chemokine fractalkine, which is tethered to cell surfaces, shows increased expression in human airway epithelial cells after stimulation with IFN-γ and may be involved in recruitment and adhesion of monocytes, T lymphocytes, and natural killer cells to epithelial surfaces (Fujimoto et al., 2001). Whether fractalkine or its receptor CX3CR1 is increased in COPD is not yet known.

VIII. Cytokines

Since chronic inflammation is a prominent feature of COPD, it is not surprising that cytokines play a key role in its pathophysiology. Several cytokines have been implicated in COPD (Chung, 2001).

A. Tumor Necrosis Factor-α

1. Increased Production. TNF-α is present in high concentration in the sputum of COPD patients (Keatings et al., 1996), particularly during exacerbations (Aaron et al., 2001). There is also an increase in soluble TNF receptors in sputum (Vernooy et al., 2002). Measurement of TNF-α in sputum is difficult, since dithiothreitol interferes with the antibody-based assay, and it is only reliably detected when sputum supernatant is prepared by ultracentrifugation.

There has been considerable interest in polymorphisms of the TNF-α gene in the pathogenesis of COPD, especially the A/G polymorphism at −308 (TNF2). This polymorphism has been associated with enhanced TNF transcription and therefore production of greater concentrations of TNF-α than of controls following activation (Kroeger et al., 2000). This TNF2 polymorphism has been associated with increased susceptibility of COPD in some studies (Huang et al., 1997; Kucukaycan et al., 2002; Sakao et al., 2002), but not in others (Higham et al., 2000; Ishii et al., 2000b; Ferrarotti et al., 2003). This may be related to the type of COPD studied and has been associated with more severe disease (Keatings et al., 2000) and with extent of emphysema on high-resolution computed tomography scan (Sakao et al., 2002). These discrepancies may reflect ethnic variations in the pathogenesis of COPD or may suggest that a combination of predisposing factors is required to develop the disease.

TNF-α is normally synthesized as a 26-kDa precursor (pro-TNF-α) that is stored in a membrane-bound form. On stimulation with an appropriate stimulus (such as lipopolysaccharide), the precursor is converted to pro-TNF-α, a 17-kDa, biologically active form, ready for release. Pro-TNF-α is finally converted to active TNF-α by a membrane-bound metalloproteinase called TNF-α converting enzyme (TACE), although other matrix metalloproteinases also have a greater or lesser degree of TNF-α converting potential (Gearing et al., 1994). In vitro MMP-12 also releases active TNF-α from a synthetic pro-form, and murine models suggest that active TNF-α release from macrophages after acute smoke exposure is dependent on both TACE and MMP-12 (Churg et al., 2003).

Serum concentrations of TNF-α and stimulated TNF-α production from peripheral blood monocytes are increased in weight-losing COPD patients, suggesting that it may play a role in the cachexia of severe COPD (Di Francia et al., 1994; de Godoy et al., 1996; Pitsiou et al., 2002). In one study (Calikoglu et al., 2004), serum concentrations of TNF-α were increased compared with normal subjects, although this difference is not statistically significant, but they increased significantly during exacerbations when there was a correlation with plasma leptin concentrations. This may indicate that the increased TNF-α formation during exacerbations may contribute to loss of body weight. Plasma concentrations of TNF-α are also increased slightly in COPD patients compared with normal controls during exercise, but this is not associated with any increase in TNF-α expression in skeletal muscle (Rabinovich et al., 2003).

2. Effects. Studies with TNF receptor knockout suggest that TNF may account for 70% of cigarette smoke-induced emphysema in mice (Churg et al., 2004). TNF-α activates NF-κB, which switches on the transcription of inflammatory genes, including cytokines, chemokines, and proteases, in epithelial cells and macrophages. It similarly activates p38 MAP kinase, which in turn may activate a similar array of genes and may interact with the NF-κB pathway. This suggests a role for TNF-α in
amplifying the inflammation of COPD. TNF-α has a broad spectrum of inflammatory effects relevant to COPD, resulting in activation of neutrophils, monocytes, macrophages, epithelium, mucus secretion, and destruction of lung parenchyma through release of proteinases (Fig. 13).

TNF-α inhibits the expression of skeletal muscle proteins via activation of NF-κB (Langen et al., 2001). This suggests that inhibitors of TNF-α might be useful in reversing the skeletal wasting seen in COPD as well as reducing the airway inflammatory response (Barnes, 2001a).

3. Inhibition. Blocking antibodies (such as infliximab) and soluble receptors (such as etanercept) have proven to be very useful in the treatment of severe rheumatoid arthritis and inflammatory bowel disease, even in patients who are relatively unresponsive to steroids (Palladino et al., 2003). TNF-α inhibitors are therefore a logical approach to COPD therapy, and clinical trials are now underway. However, there are some concerns about potential long-term adverse effects, such as increased susceptibility to infections. Because antibody-based therapies have to be given by injection, small molecule inhibitors of TNF-α would be beneficial, because they may be given orally. TACE is a matrix metalloproteinase-related enzyme critical for the release of TNF-α from the cell surface. Small-molecule TACE inhibitors are in development as oral TNF-α inhibitors, but cell-associated TNF-α may exert residual effects (Rabinowitz et al., 2001).

B. Interleukin-1β

IL-1β has similar actions to TNF-α and is a potent activator of alveolar macrophages from COPD patients (Russell et al., 2002b). Bronchial epithelial cells in culture release more IL-1β than do cells from normal subjects after stimulation with cigarette smoke (Rusznak et al., 2000). However, elevated levels of IL-1 in COPD have not yet been reported. IL-1 receptor antagonist (IL-1RA) is an endogenous inhibitor of IL-1 effects and has been reported to be reduced in asthma. In COPD macrophages, a reduced secretion of IL-1RA compared with normal macrophages in response to Chlamydia infection has been described (Rupp et al., 2003). IL-1β stimulates the expression of elastolytic MMPs, including MMP-9, from various cell types (Kusano et al., 1998).

Recently, the role of IL-1β in the development of emphysema has been studied comparing an IL-1β type 1 receptor knockout mouse with double-TNF-α receptor-deficient, combined IL-1β- and TNF-α receptor-deficient, and wild-type mice after intratracheal instillation of porcine pancreatic elastase. Emphysema continued to progress for more than 10 days after clearance of the elastase. After 21 days, emphysema was reduced in all knockout mice compared with the wild strain. The combined IL-1β and TNF-α receptor-deficient mice showed a significant reduction in emphysema compared with the wild strain and also the single knockout animals. The authors (Lucey et al., 2002) suggest that 27% of emphysema could be related to the IL-1β type 1 receptor, 36% to TNF-α type 1 and 2 receptors, and 81% to combination of the two receptor groups, which is more than additive. This animal model suggests that both IL-1β and TNF-α are important in the pathogenesis of COPD with some evidence of a synergistic interaction.

C. Interleukin-6

IL-6 concentrations are increased in induced sputum, bronchoalveolar lavage, and exhaled breath condensate of COPD patients, particularly during exacerbations (Bhowmik et al., 2000; Song et al., 2001; Bucchioni et al., 2003). IL-6 is also increased in the plasma of COPD patients (Debigare et al., 2003; Godoy et al., 2003; Hageman et al., 2003), especially during exacerbations (Wedzicha et al., 2000). Monocytes from COPD patients release more IL-6 in response to stimulation with LPS than cells from normal subjects (Aldonyte et al., 2003). IL-6 is a marker of inflammation, since it is activated by
NF-κB, but its role in inflammation is uncertain, as it has both anti-inflammatory and proinflammatory actions and its effects may be determined by the presence of other cytokines.

D. Interleukin-9

IL-9 is a cytokine that is normally released from T helper 2 cells and has an amplifying effect on allergic inflammation (Shimbara et al., 2000). Surprisingly, it shows a marked increase in expression in T lymphocytes in bronchial biopsies of patients with COPD (Panzner et al., 2003). IL-9 is a potent inducer of mucus production, causing increased expression of the MUC5AC gene (Reader et al., 2003).

E. Granulocyte-Macrophage Colony Stimulating Factor

The concentrations of GM-CSF in BAL fluid are increased in stable COPD but markedly elevated during exacerbations (Balbi et al., 1997). GM-CSF is important for neutrophil survival and priming, and it may play an enhancing role in neutrophilic inflammation. Like other proinflammatory cytokines, it is predominantly regulated by NF-κB. Interestingly, the spontaneous and induced secretion of GM-CSF from alveolar macrophages of COPD is no different than that from macrophages of smokers, whereas there is a marked increase in TNF-α, IL-8, and MMP-9 (Culpitt et al., 2003). Furthermore, GM-CSF secretion is suppressed by a corticosteroid, whereas the secretion of the other cytokines appears to be steroid resistant.

F. Interleukin-10

IL-10 is a potent anti-inflammatory cytokine that is released from monocytes and alveolar macrophages in response to inflammatory stimuli. IL-10 secretion is markedly reduced in alveolar macrophages from patients with asthma (Barnes, 2001b), and its concentrations are reduced in sputum of patients with asthma and COPD, suggesting that a similar abnormality may apply in COPD (Takanashi et al., 1999). IL-10 production appears to be increased in macrophages from normal smokers (Lim et al., 2000b), but it is not certain whether macrophages from COPD patients show a relatively reduced production, as in asthma, which may help to amplify inflammation. However, bronchial biopsies from COPD patients show increased IL-10 expression (Panzner et al., 2003).

IL-10 has therapeutic potential in COPD, as it has a broad spectrum of anti-inflammatory effects, many of which are mediated via inhibition of NF-κB via an effect on signal transducer and activator of transcription 3 (Williams et al., 2004). IL-10 suppresses the release of MMP-9 from monocytes of COPD patients and at the same time stimulates the release of its major endogenous inhibitor, tissue inhibitor of matrix metalloproteinases (TIMP-1) (Lacraz et al., 1995; Mostafa et al., 2001).

G. Interleukin-12

There is increased expression of IL-12 in bronchial biopsies of COPD patients accompanied by an increase in phosphorylated signal transducer and activator of transcription 4 (Di Stefano et al., 2004). By contrast, the transcription factor T-bet, which regulates IFN-γ expression in response to IL-12 stimulation, did not increase.

H. Interleukin-13

Overexpression of IL-13 and also interferon-γ in murine lungs unexpectedly results in emphysema that is mediated by increased expression of MMPs and cathepsins (Wang et al., 2000; Zheng et al., 2000). There is also an association between a promoter polymorphism in the IL-13 gene and COPD, as has been seen for asthma (van der Pouw Kraan et al., 2002). There is increased expression of IL-13 in bronchial biopsies of smokers with mucus hypersecretion compared with normal smokers (Miotto et al., 2003). This may be consistent with the fact that IL-13 is a potent stimulant of mucus secretion and stimulates the differentiation of goblet cells via activation of EGFR (Shim et al., 2001).

I. Interleukin-17

IL-17 is a cytokine that releases CXC chemokines from airway epithelial cells (Prause et al., 2003) but is not increased in sputum of COPD patients (Barczyk et al., 2003).

J. Interferon-γ

Overexpression of IFN-γ in murine lungs results in emphysema (Wang et al., 2000). There is increased expression of IFN-γ in bronchial biopsies of COPD patients (Panzner et al., 2003; Di Stefano et al., 2004). The CXCR3-positive T cells that are increased in small airways of COPD patients all express IFN-γ, and IFN-γ stimulates the expression of CXC3 ligands such as IP-10, suggesting a positive feedback loop. CD8+ IFN-γ-positive cells (Tc1 cells) are increased in the sputum of COPD patients (Tzanakis et al., 2004). An increase in IFN-γ secreting peripheral blood mononuclear cells has also been described in COPD patients (Majori et al., 1999).

IX. Growth Factors

Marked structural changes are found in small airways and lung parenchyma, presumably as a result of chronic inflammation and the release of growth factors that induce fibrosis and cell proliferation.

A. Transforming Growth Factors

TGF-β1 shows increased expression in small airway epithelial cells and alveolar macrophages of patients with COPD and might play a role in the characteristic fibrosis in small airways (de Boer et al., 1998; Takizawa...
et al., 2001). However, no increase in TGF-β has been found in large airway biopsies from COPD patients (Aubert et al., 1994; Kokturk et al., 2003). Increased secretion of TGF-β is reported in peripheral blood monocytes from COPD patients (Hodge et al., 2003). Increased TGF-β expression in peripheral lung tissue of COPD patients has been correlated with immunoreactivity for 4-hydroxy-4-nonenal, a marker of oxidative stress (Rahman et al., 2002). TGF-β induces the release of collagen tissue growth factor (CTGF), which mediates the fibrosis response to TGF-β (Ihn, 2002). In a human epithelial cell line, latent adenovirus infection (which has been associated with COPD) induces increased expression of both TGF-β and CTGF (Ogawa et al., 2004). TGF-β is secreted in a latent form that is inactive but is potently activated by MMP-9 (Yu and Stamenkovic, 2000); this may be mediated via MMP-9-induced proteolytic cleavage of latent TGF-binding protein-1, resulting in release of active TGF-β (Dallas et al., 2002). This mechanism therefore could be a link between elastolysis induced by MMP-9 and simultaneous production of fibrosis by activation of TGF-β (Fig. 14). Alveolar macrophages recognize apoptotic cells via phosphatidylserine receptors, and this interaction results in the expression of TGF-β1, which exerts both an anti-inflammatory action and promotes fibrosis (Huynh et al., 2002).

TGF-β potently down-regulates β2-adrenergic receptors by inhibiting gene transcription in human cell lines (Mak et al., 2000; Takeyama et al., 2001) and markedly reduces the bronchodilator response to β-agonists in airway smooth muscle in vitro (Ishikawa et al., 2003). A polymorphism in the promoter of the TGF-β1 gene (−509T) that is associated with increased production of TGF-β has been associated with severe asthma (Pulley et al., 2001; Silverman et al., 2004). A polymorphism in the coding region of TGF-β1 that is associated with increased TGF-β production surprisingly appears to be less commonly associated with COPD, indicating a possible protective role of TGF-β (Wu et al., 2004).

Small-molecule inhibitors of TGF receptor kinase are now in development, and TGF-β antagonists (DaCosta et al., 2004) might be a means of preventing the small airway fibrosis that is characteristic of COPD.

Alveolar macrophages produce TGF-α in much greater amounts than they do TGF-β (Toossi et al., 1996), and this may be a major endogenous activator of EGFR that plays a key role in regulating mucus secretion in response to many stimuli, including cigarette smoke. Cigarette smoke activates TACE in airway epithelial cells, which results in the shedding of TGF-α and the activation of EGFR, resulting in increased mucus secretion (Shao et al., 2004). The mucus secretory response to cigarette smoke is inhibited by knockdown of TGF-α and TACE by interference RNA.

**B. Epidermal Growth Factor**

EGF and TGF-α activate EGFR, which appear to play a key role in the regulation of mucus secretion, expression of mucin (MUC) genes, and differentiation of mucus-secreting cells (Nadel and Burgel, 2001). EGFR are involved in the increased mucus secretory response to oxidative stress and cigarette smoke (Takeyama et al., 1999, 2000, 2001; Basbaum et al., 2002) (Fig. 15).

This suggests that inhibitors of EGFR may be of potential value in the treatment of the mucus hypersecretion of COPD. Several small-molecule inhibitors of EGFR tyrosine kinase, such as gefitinib, are now developed for the treatment of nonsmall-cell lung cancer (Wakeling, 2002). These treatments appear to be well tolerated and therefore might be suitable for the treatment of mucus hypersecretion.

**C. Vascular-Endothelial Growth Factor**

VEGF is a major regulator of vascular growth and is likely to be involved in the pulmonary vascular remod-
eling that occurs as a result of hypoxic pulmonary vasoconstriction in severe COPD (Wagner, 2003). There is increased expression of VEGF in pulmonary vascular smooth muscle of patients with mild and moderate COPD, but paradoxically, a reduction in expression in severe COPD with emphysema (Santos et al., 2003). Inhibition of VEGF receptors in rats using a selective inhibitor induces apoptosis of alveolar endothelial cells resulting in emphysema (Kasahara et al., 2000), and this appears to be associated with oxidative stress (Tuder et al., 2003). Interestingly, the concentration of VEGF is increased in induced sputum of patients with asthma and chronic bronchitis but is significantly reduced in patients with COPD with emphysema (Kanazawa et al., 2003a,b). A common polymorphism of the VEGF gene that is associated with decreased VEGF expression (C936T) is not associated with any increased risk of COPD (Sakao et al., 2003).

D. Fibroblast Growth Factors

Fibroblast growth factor (FGF)-1, FGF-2, and FGF receptors are abnormally expressed in airway and pulmonary vascular smooth muscle and airway epithelial cells in peripheral lung of patients with COPD (Kranenburg et al., 2002). The increased expression of FGF is particularly correlated with vascular remodeling. Blocking endogenous FGF through transgenic expression of a soluble receptor is associated with emphysema in developing mice, but it has no effect in adult animals (Hokuto et al., 2003).

X. Proteases

It has long been proposed that various proteases break down connective tissue components, particularly elastin, in lung parenchyma to produce emphysema and that there is an imbalance between proteases and endogenous antiproteases that should normally protect against protease-mediated effects (Fig. 16). Elastin may be the most important target for these enzymes, because there is a loss of elasticity in the lung parenchyma in patients with emphysema, and elastin cannot be regenerated in an active form. Evidence for elastin degradation in COPD is provided by the increased excretion of desmosine, derived from elastin cross-links, in smokers with rapid decline in lung function compared with those experiencing a normal decline (Gottlieb et al., 1996). Although early attention was focused on neutrophil elastase, many other proteases that have the capacity to degrade elastin have now been implicated (Stockley, 2001).

A. Neutrophil Elastase

There has been particular emphasis on the role of NE since patients with inherited α1-antitrypsin (α1-AT) deficiency (PiZZ) were shown to develop early-onset emphysema. Furthermore, the demonstration that α1-AT may be inactivated by cigarette smoke exposure raised the possibility that neutrophil elastase may also be important in smokers with normal plasma α1-AT concentrations. This was supported by animal models in which tracheal instillation of NE induces emphysema, infiltration of neutrophils (Senior et al., 1977), and immunocytochemical localization of NE on elastin fibers in the lung parenchyma of patients with emphysema (Damiano et al., 1986). NE (E.C.3.4.21.37) is a serine protease that is inhibited by α1-AT in the lung parenchyma. It is stored in azurophilic granules in neutrophils, and it may be expressed on the cell surface in cells primed by cytokines (Owen et al., 1997). There is an increase in the
amount of NE/α1-AT complexes in bronchoalveolar lavage fluid of COPD patients who are normal smokers (Yoshioka et al., 1995), and this is correlated with the rate of decline in FEV₁ (Betsuyaku et al., 2000).

NE has subsequently been shown to have several other actions relevant to its potential role on COPD. It is a potent mucus secretagogue of submucosal gland cells and goblet cells (Sommerroff et al., 1990; Takeyama et al., 1998; Nadel, 2000). NE induces the expression of MUC5AC in an epithelial cell line, and this mechanism appears to be dependent on the generation of reactive oxygen species (Voynow et al., 1999; Fischer and Voynow, 2002). NE also induces the expression of some cytokines, including IL-8 in airway epithelial cells (Nakamura et al., 1992). NE cleaves the phosphatidylserine receptor on macrophages, thus impairing the macrophages' ability to clear apoptotic cells (Vandivier et al., 2002).

On the other hand, NE also inactivates CD14, a cell surface receptor for lipopolysaccharide, thus reducing the inflammatory response to endotoxin (Le Barilie et al., 1999). NE is likely to play a role in host defense, and NE<sup>−/−</sup> mice have increased susceptibility to overwhelming Gram-negative bacterial infections, but they do not appear to have any increase in spontaneous infections (Belaouaj et al., 1998; Shaprio, 2002).

The role of NE in COPD will only be established when the effect of NE inhibitors has been studied clinically (Ohbayashi, 2002). In guinea pigs exposed to cigarette smoke, a NE inhibitor markedly reduced emphysema and the neutrophil inflammatory response (Wright et al., 2002). Deletion of the gene for NE in mice (NE<sup>−/−</sup>) significantly protects the animals against the development of cigarette smoke-induced emphysema and also results in a reduction in the numbers of neutrophils in the lungs (Shapiro et al., 2003). Although several NE inhibitors have been tested in humans, there are few results reported. It is not certain whether the drugs failed or the clinical trials were not adequately designed. The NE inhibitor MR889 had no effect on urinary desmosine in unselected COPD patients, but a small reduction was seen in patients with a relatively mild disease load (Luisetti et al., 1996). Several small-molecule NE inhibitors are apparently in clinical development for COPD (Ohbayashi, 2002; Wark, 2002). The macrolide antibiotics erythromycin and florithromycin have also been shown to inhibit NE activity (Gorrini et al., 2001), and this might account for their beneficial effect on mucus hypersecretion (Goswami et al., 1990). However, a trial of clarithromycin for 12 weeks failed to reduce NE concentrations or neutrophil count in sputum of COPD patients (Banerjee et al., 2004).

B. Other Serine Proteases

Neutrophils also store two other serine proteases, cathepsin G and proteinase 3, in their specific granules (Rao et al., 1991). These other serine proteases have similar properties to NE and induce mucus secretion in a similar way (Sommerroff et al., 1990; Witko-Sarsat et al., 1999). Proteinase-3 is potently expressed on the surface of neutrophils after activation with cytokines (Campbell et al., 2000). Proteinase 3 is potently inhibited by α1-AT (Duranton and Bieth, 2003), but it is only poorly inhibited by SLPI in comparison to NE, and indeed proteinase 3 destroys the activity of SLPI (Rao et al., 1993). The neutrophil elastase inhibitors currently in development also inhibit these other serine proteases (Ohbayashi, 2002).

C. Cysteine Proteases

Cysteine proteases (cathepsins) may also be involved in COPD (Chapman et al., 1997; Turk et al., 2001). Cathepsin S expression is induced by IFN-γ in several cell types, including smooth muscle cells. Overexpression of IFN-γ induces emphysema in mice, and there is increased expression of cathepsins B, D, H, L, and S (Wang et al., 2000). Cathepsin inhibitors markedly reduce the emphysema induced in IL-13 transgenic mice, indicating the elastolytic potential of this cathepsin (Zheng et al., 2000). Several other cathepsins also have elastolytic activity, including cathepsins B, K, and L, which are expressed in alveolar macrophages (Reddy et al., 1995; Punturieri et al., 2000) and cathepsin W in CD8<sup>+</sup> T cells (Linnevers et al., 1997). Cathepsins B, L, and S inactivate SLPI (Taggart et al., 2001).

The role of cathepsins in COPD is uncertain. Increased concentrations of cathepsin L have been detected in BAL fluid of patients with emphysema (Takeyabu et al., 1998), and alveolar macrophages from patients with COPD secrete more cysteine protease activity than macrophages from normal smokers or nonsmokers (Russell et al., 2002b). The endogenous inhibitors of cathepsins are cystatins and stefins, but little is known about their role in COPD. Cystatin C concentrations are increased in BAL fluid of patients with COPD (Takeyabu et al., 1998).

D. Matrix Metalloproteinases

MMPs are a large family of zinc-dependent proteases that regulate the destruction of extracellular matrix components (Stamenkovic, 2003). It is now increasingly recognized that MMPs also play a key role in the regulation of cytokines, chemokines, and growth factors. There is increasing evidence for a role for MMPs in COPD (Shapiro and Senior, 1999). In patients with emphysema, there is an increase in bronchoalveolar lavage concentrations and macrophage expression of MMP-1 (collagenase) and MMP-9 (gelatinase B) (Finlay et al., 1997; Betsuyaku et al., 1999; Culpiitt et al., 1999). There is an increase in activity of MMP-9 in the lung parenchyma of patients with emphysema (Ohnishi et al., 1998), and this is correlated with FEV₁ (Kang et al., 2003). MMP-1 expression is also increased in the lungs of patients with emphysema, with predominant localiza-
tion to type II pneumocytes (Imai et al., 2001). Alveolar macrophages from normal smokers express more MMP-9 than those from normal subjects (Lim et al., 2000b), and there is an ever greater increase in cells from patients with COPD (Russell et al., 2002a), which has greatly enhanced elastolytic activity (Russell et al., 2002b). Indeed, using the MMP inhibitor marimastat, it was shown that MMPs account for most of the elastolytic activity released from alveolar macrophages from COPD patients over prolonged periods (Russell et al., 2002b). MMP-9 and the ratio of MMP-9 to TIMP-1 are increased in induced sputum of patients with COPD (Cataldo et al., 2000; Beeh et al., 2003a). MMP-8 and MMP-9 do not only act as secreted enzymes, but they are also bound to cells where they exert elastolytic activity. Thus, approximately 80% of the MMP-8 and MMP-9 synthesized by neutrophils remains associated with the surface and is not neutralized by TIMPs, so they may play a critical role in elastolysis (Owen et al., 2003, 2004).

The interest in MMPs has been heightened by the demonstration that emphysema induced by chronic cigarette exposure is prevented in MMP-12−/− (macrophage metalloelastase) mice (Hautamaki et al., 1997). In MMP-12−/− mice, emphysema induced by IL-13 and IFN-γ overexpression is reduced (Wang et al., 2000; Zheng et al., 2000), and there is a marked reduction in the recruitment of monocytes into the lung. This may be because MMPs generate chemotactic peptides that promote macrophage recruitment to the parenchyma and airways. MMPs activate the latent form of TGF-β to its active form (Dallas et al., 2002). In addition, mice in which the integrin αvβ6 is deleted (Itgb6-null mice) fail to activate TGF-β and develop age-related emphysema, which is prevented in MMP-12−/− mice and by overexpression of TGF-β1 (Morris et al., 2003). This suggests that TGF-β1 down-regulates MMP-12 under normal conditions, and absence of TGF-β results in excessive MMP-12 and emphysema. MMP-9−/− mice are not protected against emphysema induced by cigarette smoke, but they are protected from small airway fibrosis (Lanone et al., 2002). TGF-β1 is activated by MMP-9 (Yu and Stamenkovic, 2000); this may be mediated via MMP-9-induced proteolytic cleavage of latent TGF-binding protein-1, resulting in the release of TGF-β1 (Dallas et al., 2002). Therefore, this mechanism could be a link between elastolysis induced by MMP-9 and simultaneous production of fibrosis by activation of TGF-β1 (Fig. 14). Thus, MMP-12 is a prominent MMP in the mouse, and, while present in humans, it does not appear to be as important as MMP-9.

Various polymorphisms of MMP-1, MMP-9, and MMP-12 have been associated with emphysema (Mine-matsu et al., 2001; Joos et al., 2002; Wallace and Sandford, 2002). The increasing evidence for the involvement of MMP-9 in COPD suggests that inhibitors would be of value in preventing emphysema (Belvisi and Bottomley, 2003). A nonselective MMP inhibitor inhibits the development of emphysema in cigarette smoke-exposed guinea pigs (Selman et al., 2003). Nonselective small-molecule MMP inhibitors, such as marimastat, appear to have considerable musculoskeletal side effects. It is possible that side effects could be reduced by increasing selectivity for specific MMPs or by targeting delivery to the lung parenchyma. Another approach is to reduce the expression of MMP-9 in pulmonary cells. Treatment of emphysema patients with retinoic acid appears to reduce the concentration of MMP-9 in circulation (Mao et al., 2003). TIMPs may also be used therapeutically, particularly if engineered for greater stability (Nagase and Brew, 2003).

E. Antiproteases

Normally, proteases are counteracted by an excess of endogenous antiproteases. The major inhibitors of serine proteases are α1-AT in lung parenchyma and airway epithelium-derived SLPI in the airways. Other serine protease inhibitors include elafin and α1-antichymotrypsin. Serine protease inhibitors inactivate NE and other serine proteases such as proteinase-3 (Rooney et al., 2001).

1. α1-Antitrypsin. Multiple genetic variants of α1-AT are now recognized that give rise to reduced circulating active α1-AT concentrations (Mahadeva and Lomas, 1998; Carrell and Lomas, 2002). The best described deficiency that results in early-onset emphysema is the ZZ type (PiZZ), in which a single amino acid substitution (Gly342→Lys) results in structural alterations in α1-AT, resulting in failure of its normal post-translational modification and secretion by hepatocytes, leading to very low plasma concentrations. Whether heterozygotes and other genetic variants that reduce circulating α1-AT concentrations to a lesser extent than the ZZ phenotype also predispose to emphysema is more debatable (Lomas and Mahadeva, 2002). ZZ α1-AT deficiency is a rare cause of emphysema accounting for less than 1% of patients, but it was proposed long ago that cigarette smoking may oxidize α1-AT, resulting in impaired antiprotease function and increased neutrophil elastase activity (Carp and Janoff, 1978). The mechanism appears to be due to oxidative stress, and oxidation of methionine at positions 351 or 358 impairs anti-NE activity of α1-AT (Taggart et al., 2000).

2. Secretory Leukoprotease Inhibitor. SLPI is the other major serine proteinase inhibitor in the airways (Vogelmeier et al., 1991). Like α1-AT, SLPI may be inactivated by oxidative stress, but also by cleavage through its active site by cathepsins L and S (Taggart et al., 2001). In patients with emphysema, proteolytic fragments of SLPI are found in BAL fluid, which contributes to the reduced anti-NE activity in these patients. This inactivation of SLPI not only impairs its anti-NE activity, but also its antimicrobial and anti-inflammatory roles. SLPI down-regulates LPS-induced TNF-α and MMP secretion from monocytes (Jin et al., 1997; Zhang
XI. Conclusions

It is clear that many inflammatory mediators are involved in the chronic inflammation and structural changes that occur in COPD. These mediators are derived not only from activated inflammatory cells, such as alveolar macrophages, neutrophils, and T lymphocytes that are recruited to the airways and lungs, but also from structural cells in the respiratory tract, including epithelial and endothelial cells and fibroblasts, which transform into mediator-producing cells. These mediators have complex effects in the airways, resulting in recruitment of inflammatory cells from the circulation, bronchoconstriction, vascular changes, mucus secretion, and structural changes in the airways and lung parenchyma. These mediators may also spill over into the systemic circulation to produce systemic changes such as cachexia and muscle wasting seen in severe disease. The therapeutic implications are that blocking the generation or receptors for these mediators will have a beneficial clinical effect, and several mediator antagonists are now in development (Barnes, 2002b). However, blocking a single mediator when so many are involved and with redundant effects, it is unlikely that this approach will produce major clinical benefit unless the mediator plays a pivotal or unique role and is high in a cascade of events. The only way to determine the importance of a mediator is to study the effect of a specific inhibitor in the disease, and this will require careful and prolonged clinical studies.

References


sputum inflammatory markers to symptoms and lung function changes in COPD exacerbations. Am J Respir Crit Care Med 169:120–128.


reactive nitrogen species production in chronic obstructive pulmonary disease and asthma. Am J Respir Cell Mol Biol 16(6):530–534.


Ishii T, Matsue T, Teramoto S, Matsuji H, Miyao M, Hosoi T, Takahashi H, Fukuchi Y, and Ouchi Y (2000b) Neither IL-1β, IL-1 receptor antagonist, nor TNF-α polymorphisms are associated with susceptibility to COPD. Respiration 69:457–561.


